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DESIGN ENGINEERING AND SUPPORT PROGRAM (DESP)

Delivery Order RZ16: Effects On Mechanical Properties From Laser Paint Stripping

James T. Coleman
Peter Sjoblom

University of Dayton Research Institute
300 College Park Avenue
Dayton, OH 45469-1035

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MATERIALS AND MANUFACTURING DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750

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14. ABSTRACT
The scope of the project was to obtain an understanding of the effects paint removal methods had on the mechanical properties of the substrate used as coverings for military vehicles. The historical data from these methods was compared to the Portable LASER System for Coating Removal (PLSCR) mechanical property test data. The approach taken to compare the different paint removal systems was to use the data from a series of mechanical property tests (tension, fatigue life, fatigue crack growth rate, hardness, and flexure), as described in the Joint Test Protocol (JTP), conducted on the metallic and non-metallic (composite) substrates used in the PLSCR project.

15. SUBJECT TERMS:
Laser paint stripping; Mechanical properties; Fatigue; 2024-T3; Dry Media Blast (DMB); Plastic Media Blast (PMB); 7075-T6; Fatigue crack growth rate; Ultimate tensile strength; Yield tensile strength; Percentage of elongation; Hardness; Flexural strength; Graphite/epoxy; Fiberglass/epoxy; Kevlar/epoxy; Nd YAG laser; CO2 laser; Flashlamp; Abrasive; Wheat starch; Statistical analysis

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1.   INTRODUCTION

This project, funded under Contract No F42620-00-D-0039, Delivery Order RZ16, evaluated the Portable Laser Coating Removal System (PLCRS) mechanical property tests results compared to the published data of other coating removal systems used by the Department of Defense (DoD). This document was submitted to the Air Force Research Laboratory Materials Laboratory (AFRL/ML). The technical points of contacts at AFRL/MLSC were Mr. Randall Straw and Mr. Thomas Naguy. The Principal Investigators at the University of Dayton Research Institute were Mr. James Coleman and Dr. Peter Sjöblom.

2.   BACKGROUND

The processes used to remove coatings from DoD equipment vary from chemical, mechanical, and high intensity light stripping, to hand sanding and scraping. The substrates primarily used on DoD equipment are metallic and composite materials. The Environmental Protection Agency (EPA) requires that the use of hazardous chemicals and materials is held to a minimum. This requirement limits the chemical and mechanical coating removal methods that can release volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) and can produce hazardous waste. The DoD is searching for an environmentally friendly paint removal method to satisfy the environment requirements without decreasing the performance of the substrate material.

3.   LITERATURE SURVEY AND DATA COMPARISON

A literature search of 74 published references was conducted on methods commonly used to remove paint from metallic and non-metallic substrates. The references were categorized by substrate and mechanical property data presented. Metallic substrate mechanical properties retrieved from the references were tensile, fatigue, and hardness. No fatigue crack growth data was found in the literature survey. Therefore, no comparison to the data generated in the Portable Laser Coating Removal System (PLCRS) program could be made. The nonmetallic substrate mechanical property commonly found in the literature was flexure strength. The paint removal methods examined were flash lamp, plastic media blasting (PMB), dry media blasting (DMB), chemical, and lasers. A catalog was created to assist in categorizing the large number of references (Appendix A).

The data gathered were compared to the test results from the (PLCRS) program. Statistical analysis was performed on the test results from the PLCRS program and compared to the literature search data gathered using the same statistical analysis approach when possible. The statistical analysis criterion was established by the Engineering and Technical Services for Joint Group on Pollution Prevention Projects Joint Test Protocol J-00-CR-017 (JTP). The JTP is designed to set the standard for acceptable mechanical tests results used to qualify materials for use in the field.

The paint-removed test results were compared to the baseline test results. The evaluation process consisted of a statistical analysis of the baseline test results compared to the paint-removed test results in each reference, where sufficiently detailed data were available, as well as from the PLCRS project.

4. STATISTICAL ANALYSIS

Statistical analysis was performed on the selected JTP test data. Confidence intervals were constructed at a 90% confidence level for the difference between baselines and de-paint treated specimens. The analyses produces an estimate of the difference between the baseline mean value and the de-paint method mean using calculated confidence intervals (CI) of 90%. A statistical significance is present if the 90% CI is completely positive or negative. A 90% CI straddled across zero represents no statistical significance.

The 90% CI calculations were completed using the (SAS) software package. This software is a widely accepted statistical software package used by statisticians. A reference to the exact methodology used can be found on page 941 of SAS/STAT Users Guide Volume 2, GLM-VARCOMP Version 6 Fourth Edition.

5. METALLIC LITERATURE SEARCH RESULTS

The primary focus of the metallic substrate literature search was on paint removal testing conducted on aluminum substrates used by the DoD. The JTP requires that four paint removal cycles be performed on the substrate before any mechanical test data is generated. Aluminum 2024-T3 (clad, bare) and 7075-T6 (clad, bare) were the materials selected for the PLCRS project so the data reference search was concentrated on those materials.

5.1 Tensile Results

The PLCRS and reference data tension results are displayed in Fig. 1. Each baseline and paint removal method was evaluated using at least ten replicates. The average tensile ultimate strength (TUS), tensile yield strength (TYS), and elongation (e) are represented in the graphs. The baseline data for the PLCRS and the reference data are the firs bar, plotted in black, in each data set. The bars right of the baseline are the test results after paint removal. Each bar is labeled with the removal method used. The reference from which the data was collected is displayed over the plot.

A statistically significant difference between the baseline and after paint removal is indicated by a '√' mark. A data set without a '√ 'mark indicates no statistical significance between the baseline and after the paint removal. The Metallic Materials Properties Development and Standardization (MMPDS) Handbook 'A' allowable level is also indicated on the charts, where applicable. Although, one cannot direct compare an A design allowable, statistically derived from 300 test results from 10 different lots, to a

mean of a handful of tests, the A allowable for the material form used is plotted in the graphs to give an indication of the relative strength level of the stripped panels.

The Al 2024-T3 bare material tension results are displayed in Figures 1, 2, and 3. The tension results (plots) for the remaining materials are located in Appendix B.

**PLCRS and Reference Data
Average TUS Results, 2024-T3 Bare**
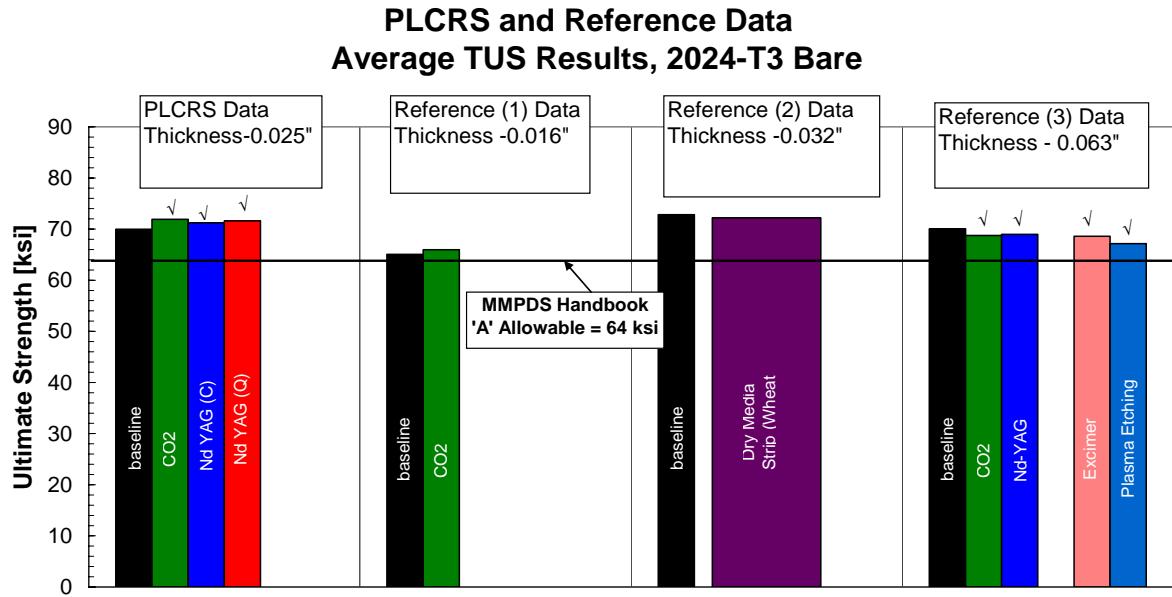
Figure 1. 2024-T3 Bare Average TUS.

**PLCRS and Reference Data
Average Yield Tensile Strength Results, 2024-T3 Bare**
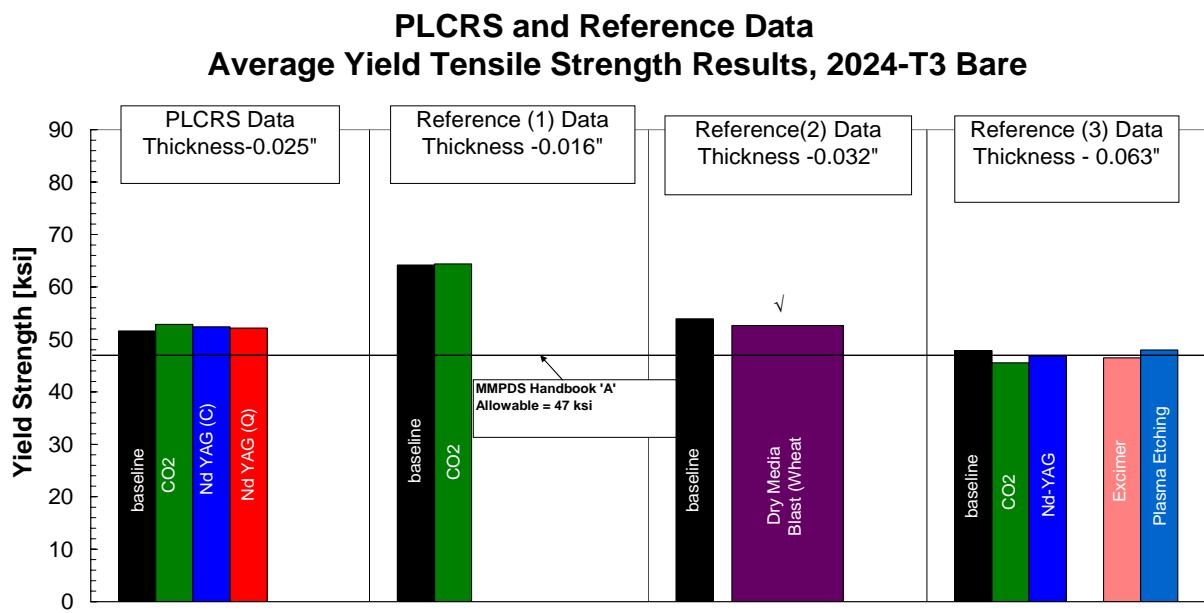
Figure 2. 2024-T3 Bare Average TYS.

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PLCRS and Reference Data
Average Percentage of Elongation Results, 2024-T3 Bare
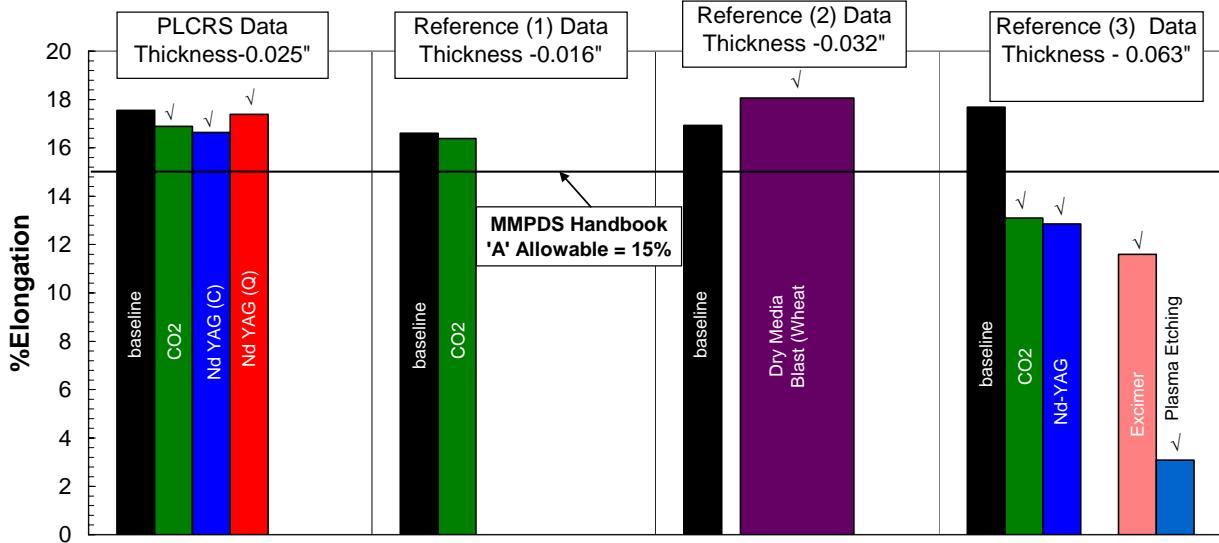
Figure 3. 2024-T3 Bare Average Elongation.

5.1.1 *2024-T3 Bare*

The paint removal method used in reference (2) was a dry media blast (DMB) while reference (1) and (3) use different lasers for removing paint from the substrate.

Strength: The PLCRS tensile properties for Al 2024-T3 bare show a statistically significant increase in ultimate strength compared to the baseline. The same trend can not be found in the reference data. The reference data either depicts a statistically significant decrease, as in reference (3), or no difference as in reference (1) and (2). Reference (2) has a statistical decrease in yield strength.

Percentage of Elongation: The percentage of elongation data from the PLCRS and reference (3) displays a statistically significant decrease when compared to the baselines used in their respective testing. There was no statistical significance difference for the elongation in the reference (1) results. Reference (2) shows a statistical increase in elongation.

5.1.2 *2024-T3 Clad*

Strength: The Al 2024-T3 clad tests results (Figures B1 thru B3 in Appendix B) display a statistically significant increase in TUS for the PLCRS Nd YAG lasers (Clean and Quantel) results; however, there is a statistically significant decrease in strength for

the carbon dioxide (CO_2) laser results. A statistically significant decrease in TYS was seen in the PLCRS CO_2 laser and DMB (2) paint removal methods. The yield strength variation for the other paint removal methods was not statistically significant.

Percentage of Elongation: The elongation for the PLCRS CO_2 and Nd YAG (Quantel) laser and DMB method show statistical difference compared to the baseline data. The PLCRS Nd YAG (Cleanlaser) elongation is statistically significant lower than the baseline data.

5.1.3 *7075-T6 Bare*

Strength: The Al 7075-T6 bare tests results (Figures B4 to B6 in Appendix B) show a statistically significant increase in TUS for the PLCRS CO_2 and Nd YAG (Quantel) laser paint removal methods and a decrease in TUS for the DMB data in reference (2). No difference in TUS using in the PLCRS Nd YAG (Cleanlaser) strength results was observed. The PLCRS laser TYS results show no statistical difference. The DMB (2) yield strength results show a statistical decrease compared to baseline data.

Percentage of Elongation: No statistical significant difference was noted.

5.1.4 *7075-T6 Clad*

Strength: The Al7075-T6 clad test results (Figures B7 to B9 in Appendix B) display an increase in the TUS for the PLCRS laser paint removal methods and a statistical decrease in the DMB (2) paint removal method. The TYS, using PLCRS lasers, did not change, but the DMB paint removal method produced a decrease.

Percentage of Elongation: The elongation results displayed no difference for the PLCRS CO_2 and Nd YAG (Quantel) laser and DMB (2) paint removal methods. The Nd YAG (Cleanlaser) laser paint removal method produced a decrease in elongation.

5.1.5 *Summary*

A summary of the PLCRS tensile results and the reference data is shown in Table 1. The space marked "+" indicates a statistically significant increase in the property, while "-" indicates a decrease. It should be noted, that although there may be a statistically significant difference at the 90% confidence level, there may not be a significant engineering difference. The differences observed are small and well within the expected scatter in material properties. This scatter has been accounted for in the design of the aircraft and should not be cause for alarm. It should also be noted that the Laser Stripping Methods showed a lesser, if any, reduction of tensile properties. The Laser Stripping Methods tensile properties are above the MMPDS 'A' allowable.

Table 1. Tensile Properties for Various Paint Stripping Methods

Paint Removal Methods	Al 2024-T3 bare Tension			Al 2024-T3 clad Tension			Al 7075-T6 bare Tension			Al 7075-T6 clad Tension		
Reference	UTS	YTS	%E	UTS	YTS	%E	UTS	YTS	%E	UTS	YTS	%E
(2), DMB (wheat starch)	-	-	NS	-	-	NS	-	-	NS	-	-	NS
(3), Plasma Etching	-	NS	-									
(3), Excimer	-	NS	-									
(1), (3), CO2 Laser	+	NS	+									
(3), Nd YAG	-	NS	-									
PLCRS												
CO2	+	NS	NS	-	-	NS	+	NS	NS	+	NS	NS
Nd YAG (Q)	+	NS	NS	+	NS	NS	+	NS	NS	+	NS	NS
Nd YAG (C)	+	NS	-	+	NS	-	NS	NS	NS	+	NS	-
NS – No Statistically Significant Difference												
- - Statistically Significant Decrease												
+ - Statistically Significant Increase												
▨ - No tabulated reference data found												

5.2 Fatigue Results

An important point to consider when viewing any fatigue data is the inherent scatter in fatigue life for any material and condition. Depending on the stress level, normal scatter in the fatigue life of metallic materials can easily range over a decade in cyclic life, witnessed in the numerous fatigue publications such as the MMPDS handbook. Differences in fatigue life of 20% are well within the norm, particularly when fatigue stresses approach the endurance strength of the material. In general, fatigue data is assumed to follow a log-normal distribution and therefore plotted and analyzed in terms of the log cycles. Thus, differences in cyclic lives of 20% and perhaps even 50%-60%, while statistically significant, may not be as significant from an engineering standpoint. Such debits or variability in fatigue life are generally design specific and best left to the design engineer to ascertain whether slight decreases in life are significant from an engineering standpoint.

The PLCRS and the reference fatigue data are displayed as bar charts in Figures 4 and 5. The average cycles-to-failure of at least five replicates for each baseline and paint removal method are presented in the graphs. The brackets on each bar represent the observed cycles-to-failure range of the replicates tested at the given stress level. The baseline data for the PLCRS and the reference data is the black bar that appear to the left in each plot. The bars next to the baseline information are the paint removal test results labeled by the removal method. The report reference number is displayed over the bar. A statistical significant difference is indicated by a '√' mark. A data set without a '√'mark indicates no statistical difference at a 90% confidence level.

The 2024-T3 clad material fatigue results are displayed in Figures 4 and 5. The fatigue results for the remaining materials are located in Appendix C (Figures C1 to C3).

PLCRS Smooth Fatigue Results, 2024-T3 clad (0.025")
Paint System #05
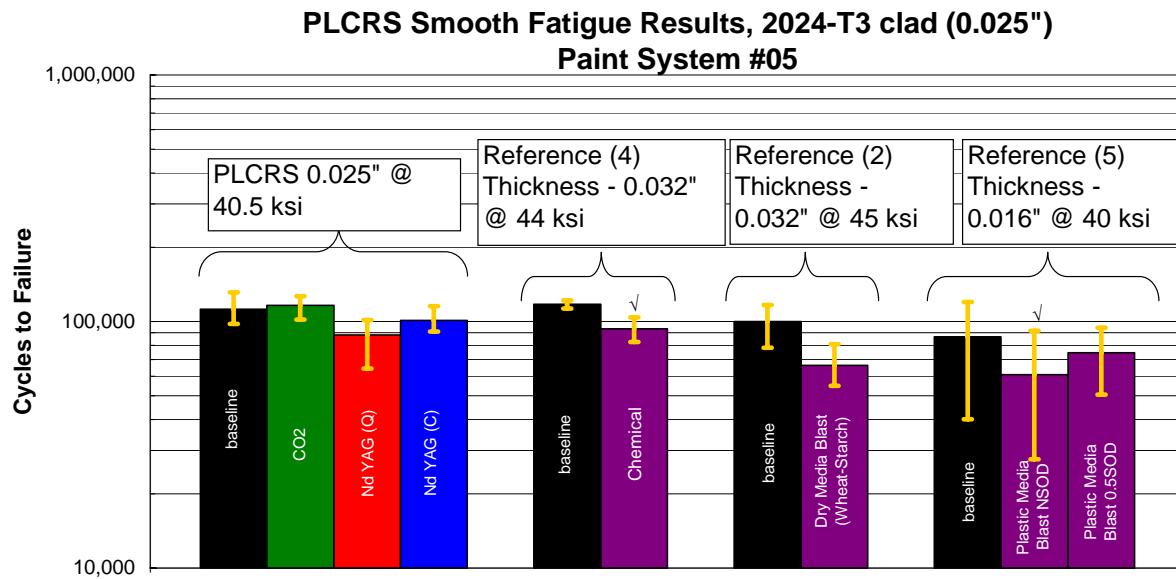
Figure 4.   **2024-T3 Clad S-N Smooth Fatigue Results. √ indicate a statistically significant difference.**

PLCRS Notch Fatigue Results, 2024-T3 clad (0.025")
**Paint System #05**
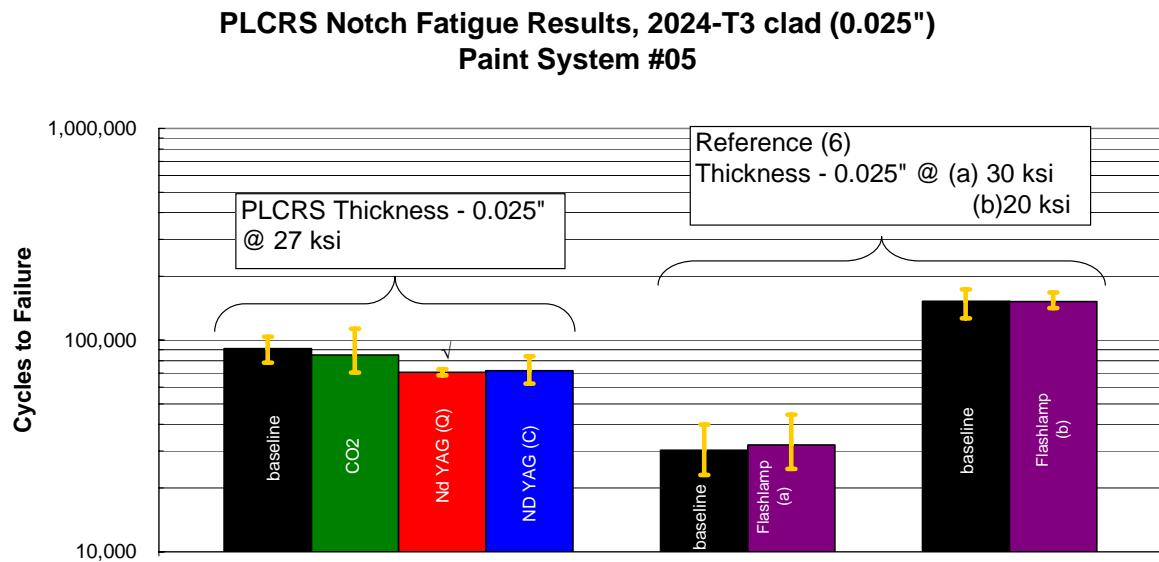
Figure 5.   **2024-T3 Clad S-N Notch Fatigue Results. √ indicate a statistical significant difference.**

5.2.1   *2024-T3 Clad Smooth Fatigue*

2024-T3 clad smooth fatigue results from the PLCRS program showed no statistically significant difference in fatigue life for the CO_2 and Nd YAG (Cleanlaser)

laser paint removal method. The Nd YAG (Quantel) laser paint and Chemical (reference (4)), and PMB NSOD (reference (5)) removal method showed a statistically significant decrease in fatigue life. Data from reference (2) (DMB) and (5) (PMB) paint removal method displayed no statistically significant difference in fatigue life.

5.2.2 *2024-T3 Clad Notch Fatigue*

The notch fatigue results for 2024-T3 clad from the Nd YAG (Quantel and Cleanlaser) paint removal method showed a statistically significant reduction in fatigue life. The CO_2 and flash lamp paint removal method (reference (6)) showed no statistically significant difference in fatigue life.

5.2.3 *7075-T6 Bare Smooth Fatigue*

The 7075-T6 bare smooth fatigue results (Figure C1 in Appendix C) for the CO_2 laser and DMB paint removal methods showed no statistically significant change in fatigue life. The Nd YAG (Quantel and Cleanlaser) laser paint removal method and chemical paint removal method resulted in a statistically significant shorter fatigue life.

5.2.4 *7075-T6 Bare Notch Fatigue*

7075-T6 bare notch fatigue results (Figure C4 in Appendix C) for the PLCRS project show a statistically significant decrease in fatigue life for the CO_2 and Nd YAG (Quantel and Cleanlaser) laser paint removal methods. No tabulated data was found for 7075-T6 bare notch fatigue in the reference data reports.

5.2.5 *7075-T6 Clad Smooth Fatigue*

7075-T6 clad smooth fatigue results (Figure C3 in Appendix C) showed no statistically significant change in fatigue life for the PLCRS lasers and PMB. Chemical strip and DMB showed a statistically significant decrease in fatigue life.

5.2.6 *7075-T6 Clad Notch Fatigue*

The notch fatigue results for 7075-T6 clad for the Nd YAG (Cleanlaser and Quantel) paint removal method showed a statistically significant reduction in fatigue life. The CO_2 and flash lamp paint removal method (reference (6)) showed no statistically significant difference in fatigue life.

5.2.7 *Summary*

A qualitative summary of the PLCRS fatigue results and the reference data is listed in Table 2. The space marked "+" indicates a statistically significant increase, while "-" indicates a statistically significant decrease. Note that all differences fall well within the normal scatter in fatigue life, approximately one decade. Therefore, the differences are not significant from an engineering standpoint.

Table 2. Fatigue Properties

Paint Removal Methods	2024-T3 Clad		7075-T6 Bare		7075-T6 Clad	
Reference	Smooth	Notch	Smooth	Notch	Smooth	Notch
(4), Chemical	-	(shaded)	-	(shaded)	-	(shaded)
(2),DMB (Wheat Starch)	-	(shaded)	(shaded)	(shaded)	-	(shaded)
(5), PMB (Plastic)	-	(shaded)	(shaded)	(shaded)	NS	(shaded)
(6), Flash lamp	(shaded)	NS	(shaded)	+	(shaded)	+
PLCRS						
CO_2	NS	NS	+	-	NS	NS
Nd YAG (Q)	-	-	-	-	NS	-
Nd YAG (C)	NS	-	-	-	NS	-
NS – No Statistically Significant Difference						
- Statistically Significant Decrease						
+ Statistically Significant Increase						
(shaded) - No tabulated reference data found						

5.3   Fatigue Crack Growth Rate (FCGR) Testing

Fatigue crack growth rate (FCGR) data aid in determining the life of a component containing cracks, as well as determining inspection intervals for the component. If crack growth rates are increased significantly by a process such as paint removal, the inspection interval may have to be reduced, leading to more frequent inspections. However, if crack growth rates are not significantly affected, the original inspection intervals are presumably still appropriate. As the crack length increases during fatigue cycling, the rate of crack propagation increases (change in crack length/ change in fatigue cycles, or da/dN) due to an increase in the range of stress intensity factor, ΔK, which is a function of both crack length and stress amplitude. The magnitude of ΔK (units of ksi$\sqrt{}$in) controls the rate of crack propagation and, with the knowledge of the expected fatigue loading and material properties, one can estimate the life of a cracked structure.

The plot in Figure 6 represents typical FCGR data. This sigmoidal shaped curve has three distinct regions: Region 1 (threshold), Region 2 (linear or 'power law' region), and Region 3 (onset of fast fracture). The linear relationship between the logarithm of da/dN and the logarithm of the stress intensity range is generally modeled as a power fit to the actual data and also termed the "Paris Region" after the researcher who first identified this relationship. Data which falls above the curve in Figure 6 indicates a higher crack propagation rate and thus identified as 'Decreased Life'. Conversely, data falling below and to the right of the idealized curve would be have lower propagation rates and thus result in 'Increased Life'.
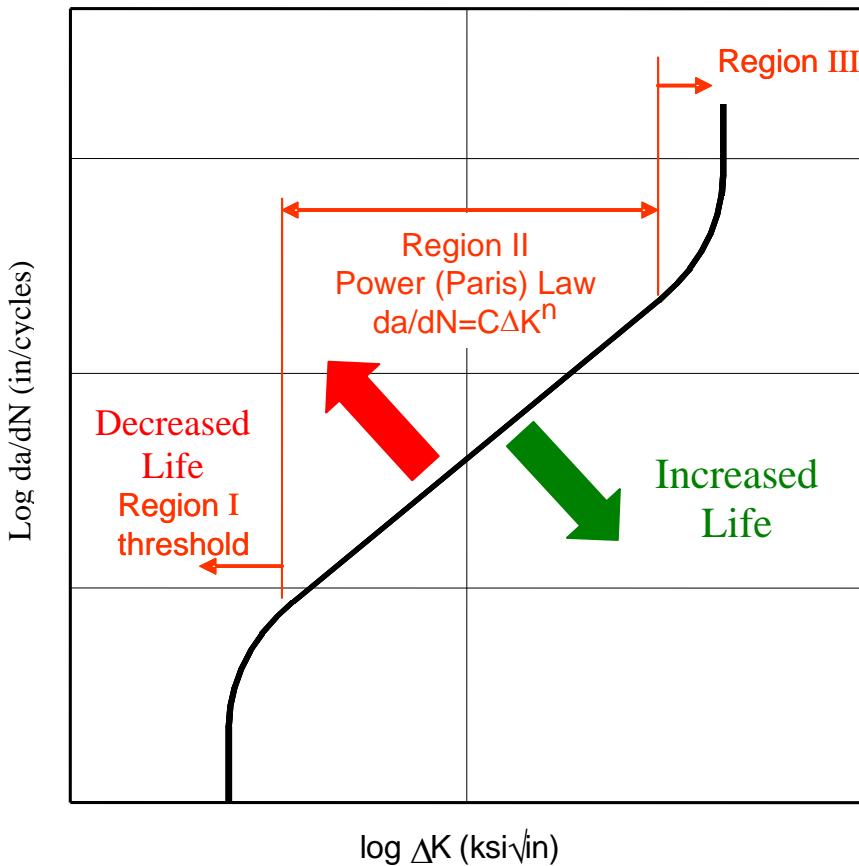
Figure 6. Example Plot of FCGR Data.

This effort evaluated the effect of the various laser paint removal processes on the crack growth rate of the metallic substrates along with baseline (un-stripped) samples. Each baseline and paint removal method had at least four replicates. An example of this for the 2024-T3 substrate is shown in Figure 7. Data for all substrates are further illustrated in Figures D1 to D4 in Appendix D.
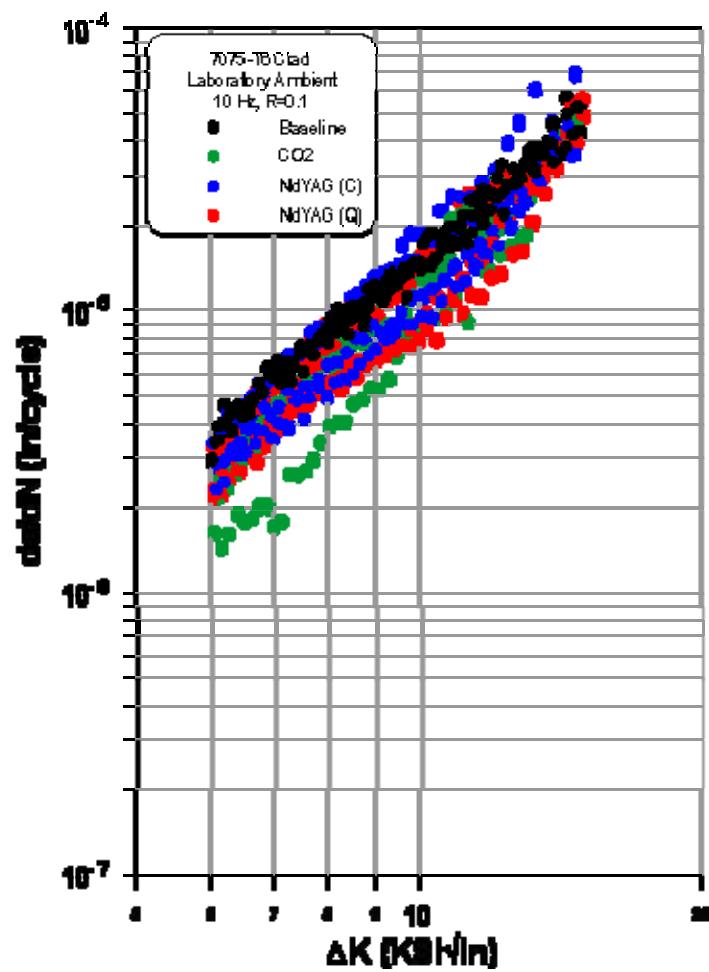
Figure 7. 7075-T6 Clad Fatigue Crack Growth Rate Test Results.

5.3.1 *FCGR Statistical Analysis*

Since any reference FCGR data could not be found in a tabulated format, it is impossible to compare reference paint removal methods with the PLCRS data. The statistical analysis performed on the PLCRS data was accomplished by first modeling the Paris region for each removal technique and substrate and examining the statistical variation in growth rates at a 90% confidence level at two distinct ΔK values: 6 and 14 ksi√in. Table 3 shows the results of this statistical analysis for all of the FCGR tests performed in the PLCRS project. The results of this analysis are further depicted graphically in Figure 8, where the Paris model is shown along with the ± 90% confidence levels. When the confidence levels of a particular data set fall below the baseline curve, a statistically significant decrease in growth rate is noted, beneficially from a life standpoint. Further more, when the confidence intervals are above the baseline, there is a statistical increase in growth rates which corresponds to a decrease in fatigue crack growth life. When the confidence intervals of two data sets overlap, no statistical differences are noted. For the 7075-T6 clad data represented in Figure 8, all the paint strip data at 6 ksi√in fall below the baseline, indicating lower growth rates. At 14 ksi√in, no statistical differences are noted between the stripped data and the baseline with the exception of the Nd YAG (Q) which is statistically lower than baseline.

Reviewing the data shown in Table 3 indicates that from a statistical standpoint, only the 2024-T3 clad data showed a decrease in growth rate resistance (i.e., higher growth rates) over baseline material. The significance of this difference (and all differences) noted in Table 3 from an engineering standpoint is discussed in the following section.

5.3.2 *FCGR Data Analysis using ASTM E647*

It is not unusual for FCGR data to show a large amount of specimen- to-specimen variability. ASTM E 647-00, *Standard Test Method for Measurement of Fatigue Crack Growth Rates[1]*, in Section 8.1 states that:

> At crack growth rates greater than 10^{-8} m/cycle, the within-lot variability (neighboring specimens) of d*a*/d*N* at a given ΔK typically can cover about a factor of two. At rates below 10^{-8} m/cycle, the variability in d*a*/d*N* may increase to about a factor of five or more due to increased sensitivity of d*a*/d*N* to small variations in ΔK. This scatter may be increased further by variables such a micro structural difference, residual stresses, changes in crack tip geometry (crack branching) or near tip stress . . .

Furthermore, the standard states:

> … the reproducibility in *da/dN* within a laboratory to average ±27% and range from ±13 to ±50%, depending on laboratory…

---

[1] Section 3, Metals Test Methods and Analytical Procedures, ASTM International, West Conshohocken, PA.

Table 3. Statistical Analysis of Fatigue Crack Growth Rate Data Results for PLCRS

Material	Paint Removal Method	ΔK ksi-$(in)^{0.5}$	Predicted Value From Model	Lower 90% Confidence Interval	Upper 90% Confidence Interval	Statistical Significance	Predicted Value – Baseline Predicted Value
2024-T3 Clad	**Baseline**	**6**	**-6.163**	**-6.184**	**-6.141**		
		14	**-4.879**	**-4.906**	**-4.852**		
	Q Laser	6	-6.137	-6.146	-6.129		0.0254
		14	-4.664	-4.676	-4.652	-	0.215
	C Laser	6	-6.126	-6.137	-6.114	-	0.0370
		14	-4.689	-4.708	-4.670	-	0.190
	CO_2	6	-6.256	-6.277	-6.235	+	-0.0930
		14	-4.783	-4.813	-4.754	-	0.0961
7075-T6 Clad	**Baseline**	**6**	**-5.366**	**-5.377**	**-5.354**		
		14	**-4.339**	**-4.354**	**-4.324**		
	Q Laser	6	-5.484	-5.508	-5.460	+	-0.118
		14	-4.435	-4.469	-4.402	+	-0.0964
	C Laser	6	-5.447	-5.473	-5.422	+	-0.0818
		14	-4.347	-4.385	-4.309	NS	-0.00786
	CO2	6	-5.584	-5.615	-5.553	+	-0.218
		14	-4.361	-4.411	-4.311	NS	-0.0220
7075-T6 Bare	**Baseline**	**6**	**-5.456**	**-5.474**	**-5.439**		
		14	**-4.259**	**-4.283**	**-4.236**		
	Q Laser	6	-5.552	-5.571	-5.533	+	-0.0955
		14	-4.250	-4.279	-4.222	NS	0.00892
	C Laser	6	-5.671	-5.707	-5.634	+	-0.214
		14	-4.202	-4.255	-4.148	NS	0.0574
	CO2	6	-5.516	-5.539	-5.492	+	-0.0591
		14	-4.244	-4.284	-4.204	NS	0.0153

+ -Statistically significant difference where the laser FCGR data lies below the baseline
- - Statistically significant difference where the laser FCGR data lies above the baseline
NS No statistical significance
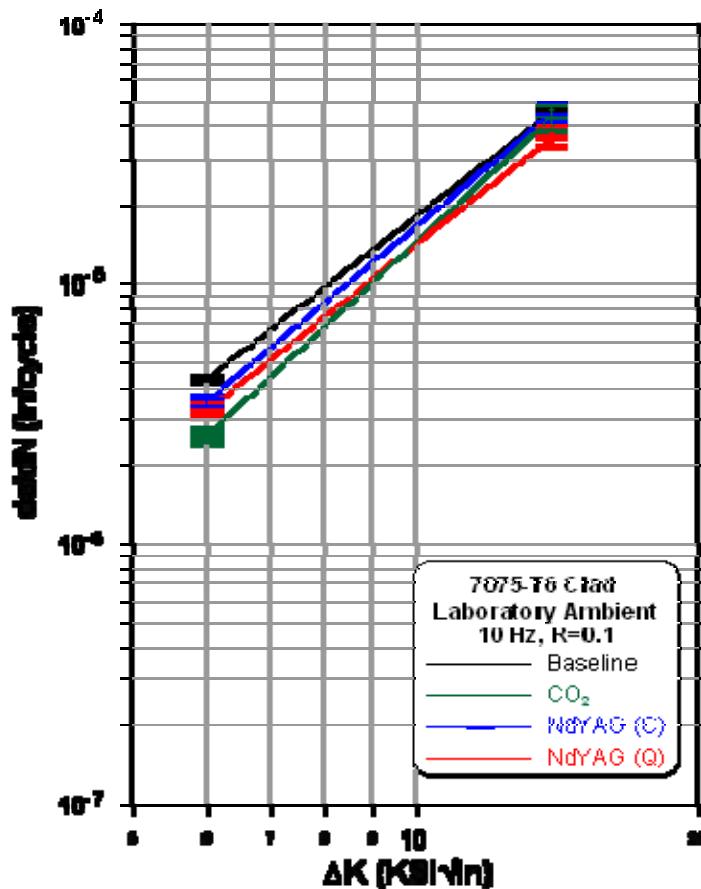
Figure 8. Statistical Representation of FCGR data for 7075-T6 Clad.

Thus the statistical differences shown in Table 3 should thus be viewed with this in mind. The data comparisons are made at the discrete ΔK levels of 6 and 14 ksi$\sqrt{\text{in}}$. The corresponding levels of da/dN are in the range of 1×10^{-4} to 1×10^{-6} in/cyc. Per the ASTM E647 standard, differences within a factor of two to five between data sets can be expected due to specimen-to-specimen variability. Therefore, since the data in Table 3 (shown as log da/dN) does not vary by more than a factor of two, differences from the baseline should be considered expected variability. As none of the data meet this criterion, there does not appear to be significant differences from an engineering standpoint between the baseline and FCGR data for any of the three examined substrates.

14

5.4 Superficial Hardness

The statistical analysis for the PLCRS hardness for 2024-T3 and 7075-T6 clad are shown in Table 4 and Figures 9 and 10. The statistical significant difference at a 90% simultaneous confidence interval for each paint removal method is indicated by a '√' mark. A data set without a '√' mark indicates no difference.

Both YAG lasers decreased the hardness; CO_2 no change for both 7075-T6 and 2024-T3.

Table 4. Statistical Analysis of Hardness

Paint Removal Method PLCRS	2024-T3 Superficial Hardness	7075-T6 Superficial Hardness
Baseline	**82.6**	**89.2**
CO_2	82.1	89.5
Nd YAG (Q)	81.5	88.1
Nd YAG (C)	80.9	88.7

PLCRS Superficial Hardness Results, 7075-T6
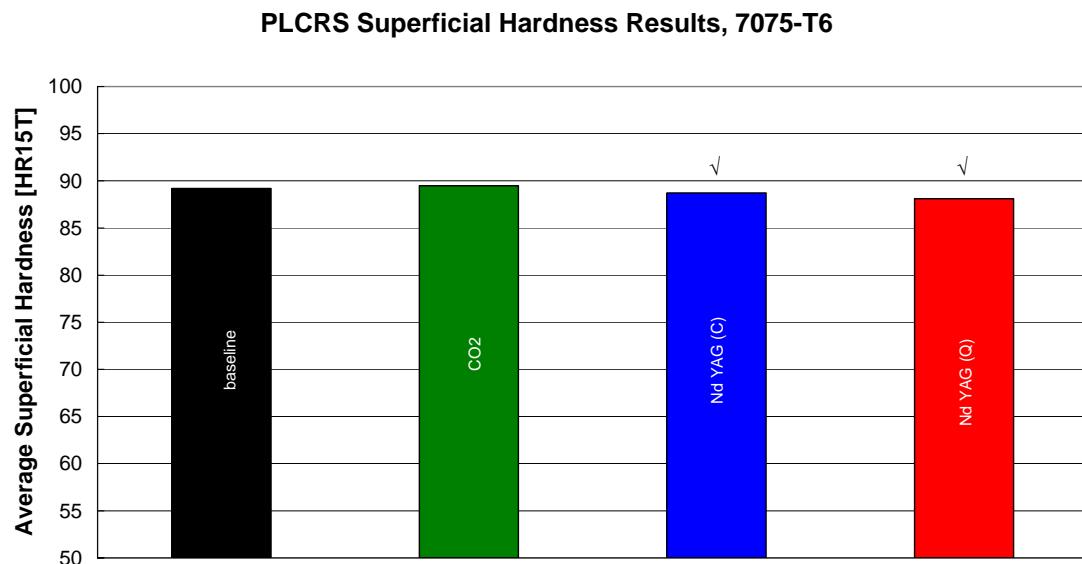
Figure 9. 7075-T6 Clad Superficial Hardness Results.

PLCRS Superifical Hardness Results, 2024-T3
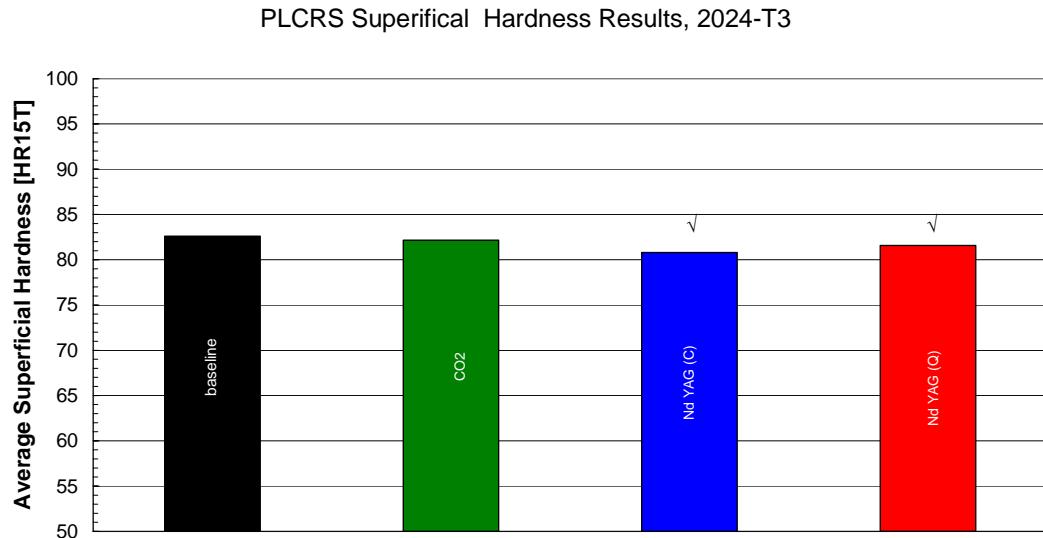
Figure 10. 2024-T3 Superficial Hardness Results. √ indicate a statistical difference at a 90% confidence level.

5.5   Conclusions/Observations

Table 5 summarizes the effects of the paint removal methods on the mechanical properties of the metallic substrates. No conclusive data depict one paint removal method to be better or worse than the others. The statistical significance presented may not represent an engineering significance. Most of the metallic tension mean levels (TUS, TYS, percentage of elongation) are above the 'A' Allowable given in the MMPDS Handbook. The most notable view from this study was how few mechanical property tests data were published on the past paint removal methods.

Table 5. Metallic Matrix for Paint Removal Methods

Paint Removal Methods	Material - 2024-T3 Bare					Material - 2024-T3 Clad					Material - 7075-T6 Clad					Material - 7075-T6 Bare 0.016"				
	Tensile			Fatigue		Tensile			Fatigue		Tensile			Fatigue		Tensile			Fatigue	
	UTS	YTS	%Elong	Smooth	Notched	UTS	YTS	%Elong	Smooth	Notched	UTS	YTS	%Elong	Smooth	Notched	UTS	YTS	%Elong	Smooth	Notched
Chemical (Reference (4))	░	░	░	░	░	░	░	░	-	░	░	░	░	NS	░	░	░	░	-	░
PMB (Reference (5))	░	░	░	░	░	░	░	░	-	░	░	░	░	NS	░	░	░	░	░	░
DMB (Wheat-Starch) (Reference (2))	-	-	NS	░	░	-	-	NS	NS	░	-	-	NS	NS	░	-	-	NS	NS	░
Flash Lamp (Reference F)	░	░	░	░	░	░	░	░	░	NS	░	░	░	░	NS	░	░	░	░	░
CO$_2$ Laser (Reference (1))	+	-	NS	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░
Plasma Etching (Reference (3))				░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░
Excimer (Reference (3))				░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░
Nd YAG Laser (Reference (3))				░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░	░
CO$_2$ Laser (AFRL Testing)	+	NS	NS	▦	▦	-	-	NS	NS	NS	+	NS	NS	NS	NS	+	NS	NS	NS	-
Nd YAG (Q) Laser (AFRL Testing)	+	NS	NS	▦	▦	+	NS	NS	-	-	+	NS	NS	NS	-	+	NS	NS	-	-
Nd YAG (C) Laser (AFRL Testing)	+	NS	-	▦	▦	+	NS	-	NS	-	+	NS	-	NS	-	NS	NS	NS	-	-

+ - Positive Statistical Significance against the baseline material data
NS - No Statistical Significance against the baseline material data
- - Negative Statistical Significance against the baseline material data
░ - Historial data not found for Statistical Analysis
▦ - No fatigue data generated

6.   COMPOSITE LITERATURE SEARCH RESULTS

The primary focus of the composite literature search was on paint removal testing conducted on composite substrates used by the DoD and in the PLCRS project The JTP requires the substrate to be run through four paint removal cycles before any mechanical testing is performed on the substrate. Graphite, fiberglass, and Kevlar epoxy were the materials selected for the PLCRS project, so the reference search focused on these materials. The paint removal methods were PMB, high intensity light (flash lamp), and hand (wet/dry) abrasive.

6.1   <u>Four-Point Flexural Testing</u>

The PLCRS and the reference data flexural results are displayed in bar charts. Each baseline and paint removal method had at least five replicates with the average flexural strength represented in the graphs. The baseline data for the PLCRS and the reference data are represented by the black bar that appears on the left in each data set. The bars next to the baseline information are the paint removal test results labeled by the removal method. The reference number is displayed over the data from which it was extracted and corresponds to the summary chart in Appendix A. A statistically significant difference in the data between the baseline and the paint removal method at a 90% simultaneous confidence interval is indicated by a '√' mark. A data set without a '√ 'mark indicates no statistical difference.

Figure 11 shows the results of the PLCRS graphite/epoxy flexural test and the reference data found for that material. Graphs for the other substrates are in Appendix E. The Nd YAG (Cleanlaser) laser results in Figure 11 shows a decrease in flexural strength in comparison to the baseline data. The reference data shows no statistical change in flexural except in the wet abrasive which showed an increase.

Figure E1 displays the PLCRS flexural strength results for the graphite, fiberglass and Kevlar epoxy laminate tests. The fiberglass results show a decrease in flexural strength for both Nd YAG lasers compared to the baseline. The Kevlar results showed no difference between the Nd YAG lasers.

Figure E2 displays the PLCRS and a PMB reference data graphite/epoxy laminate flexural strength results. Only the four cycles PMB at 38 and 60 psi showed a decrease in strength.
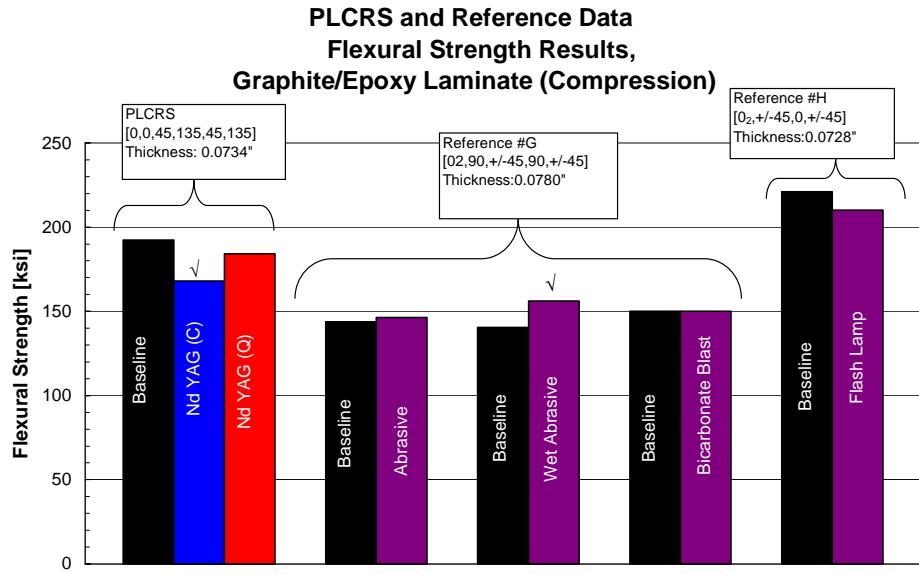
Figure 11. Graphite/Epoxy Flexural Strength Results. √ indicates a statistical significant difference at a 90% confidence level.

A matrix of the PLCRS composite flexural strength results and the reference data is presented in Table 6. The space marked "+" indicates an increase (at a 90% confidence interval) in the flexural strength, while "-" indicates a decrease.

6.2   Summary

The results of tests conducted to compare paint removal methods were inconclusive. The data did not depict one paint removal method to be better or worse than the other methods. Any indicated statistically significant difference may not represent an engineering significance. The most notable finding from this study was how few mechanical property tests data have been published on presented past paint removal methods.

Table 6. Matrix for Composite Flexural Data

Paint Removal Method	Graphite/Epoxy	Fiber Glass/Epoxy	Kevlar/Epoxy
Reference	Flexural Strength	Flexural Strength	Flexural Strength
#H Flash Lamp	NS	░	░
#E PMB (Plastic)	NS	░	░
#G Bicarbonate Blast	NS	░	░
#G Abrasive	NS	░	░
#G Wet Abrasive	+	░	░
PLCRS			
Nd YAG (Q)	NS	-	NS
Nd YAG (C)	-	-	NS
NS – No Statistical Significance			
- - Statistical decrease			
+ - Statistical increase			
░ - No tabulated reference data found			

7.   REFERENCES

1.   "Laser Paint Stripping," Head, J.D., J. Peter Niedzielski, et al., Air Force Systems Command, June 1991.

2.   "Evaluation of Envirostrip for De-painting Thin-Skinned Aluminum Alloys," Spigel, Barry S., Janet Buchingham, and Craig McClung, Air Force Material Command, October 2000.

3.   "Mechanical Behavior of Al 2024 Alloy Specimen Subjected to Paint Stripping by Laser Radiation and Plasma Etching", Sp. G. Pantelakis, *Elsevier Science* 1996.

4.   "Evaluation of the Effects of Chemical and Plastic Media Blasting Paint Removal," Alford, C., R.C. Decker, et al., Air Force Material Command, April 1994.

5.   "Evaluation of the Effects of a Plastic Bead Paint Removal Process on Properties of Aircraft Structural Materials," Sidney Childs, Air Force Systems Command, December, 1985.

6.   "Flashjet Qualification Testing for Lifecycle De-painting of Rotary Wing Fuselage Skins," Kozol, Joseph, Steven Hartle, Paul Raley, and Thomas Berkel, Naval Air Warfare Center, April 2001.

7.   "Paint Removal From Composites and Protective Coating Development," Peter W. Kopf, Air Force Systems Command, January 1991.

8.   "Acoustic Fatigue Testing of the Flashjet Process", Thomas R. Berkel, August 1999.

9.   David W. Breihan and James Reilly, "Xenon Flashlamp and Carbon Dioxide Advanced Coatings Removal Development and Evaluation Program," prepared for US Navy by McDonnell Douglas Corporation, Report #MDC 93B0341, July 1993.

APPENDIX A

**LASER PAINT STRIPPING REFERENCE LITERATURE
SUMMARY**

Laser Paint Stripping Literature Catalog

1. Alan K. Nudelman and Kenneth Abbott, "Using Plastic Media Blasting to Remove Coatings from Parts," <u>Powder Coating</u>, 485-492, April 1996.

2. Kenneth E. Abbott, "Dry Media Blasting for the Removal of Paint Coatings on Aerospace Surfaces," <u>Metal Finishing</u>, 94, 33-35, July 1996.

3. Scott Stratford, "Dry Ice Blasting for Paint Stripping and Surface Preparation," <u>Metal Finishing</u>, 98, 493-499, 2000.

4. M.W.J. van der Wielen, M. A. Cohen Stuart, G. J. Fleer, R. P. Nieuwhof, A.T.M. Marcelis, and E.J.R. Sudhölter, "A Paint Removal Concept with Side-Chain Liquid Crystalline Polymers as Primer Material," <u>Progress in Organic Coatings</u>, 41, 157-165, 2001.

5. Sp. G. Pantelakis and G. N. Haidenmenopoulos, "Effect of Novel Paint Removal Processes on the Fatigue Behavior of Aluminum Alloy 2024.", <u>Surface and Coatings Technology</u>, 105, 198-204, 1998.

6. Sp. G. Pantelakis, Th.B. Kermanidis, and G. N. Haidemonopoulos, "Mechanical Behavior of Al 2024 Alloy Specimen Subjected to Paint Stripping by Laser Radiation and Plasma Etching", <u>Theoretical and Applied Fracture Mechanics</u>, 25, 139-146, 1996.

7. B. Djurovic, É. Jean, M. Papini, P. Tangestanian, J. K. Spelt, "Coating removal from fiber-composites and aluminum using starch media blasting", <u>Wear</u>, 224, 22-37, 1999.

8. Peter W. Kopf, Jay Cheny, and John Martin," Paint Removal from Composites and Protective Coating Development," Air Force Systems Command, DTIC – ADA249238, January 1991.

9. James F. Mank, Richard J. Dick, Herbert C. Abrams, and Louis J. Nowacki, "Improved Paint Removal Technique," ALC/PPWMA, DTIC ADA136671, April 25, 1978.

10. Sidney Childers, "Evaluation of the Effects of a Plastic Bead Paint Removal Process on Properties of Aircraft Structural Materials," Air Force Systems Command, December, 1985.

11. Georges L. Chahine, Virgil E. Johnson, Jr., and Gary S. Frederick," Self Resonating Pulsed Water Jets For Aircraft Coating Removal: Feasibility Study," DTIC – ADA119114, June 1982.

12. K. G. Clark, "Compatibility of Aircraft Operational Fluids with a Graphite/Epoxy Composite-Development of an Exterior Coating System and Remover," Naval Air Systems Command, DTIC – ADA090049, June 26, 1980.

13. Thomas E. Higgins and Brian P.J. Higgins, "Industrial Process to Reduce Generation of Hazardous Waste at Department of Defense Facilities," Army Corps Engineers, DTIC – ADA165085, December 1985.

14. C.J.E. Smith and M.A.H.Hewins, "The Effect of Abrasive Blasting on Fatigue and Corrosion of an Aluminum-Copper Alloy," Royal Aircraft Establishment, DTIC – ADA154954, August 1984.

15. Naval Civil Engineering Lab, "Plastic Media Blasting Data Gather Study," DTIC – ADA176905, December 1986.

16. Joseph Kozol, Steven Thoman and Kenneth Clark, "The Effects of Plastic Media Blasting Paint Removal on the Microstructure of Graphite/Epoxy Composite Materials," Naval Air System Command, DTIC – ADA204801, October 7, 1988.

17. Lawrence M. Butkus and Gary D. Meuer, "An Evaluation of the Effects of 'Hand' Sanding and Plastic Media Blasting (PMB) Paint Removal Methods on Graphite/Epoxy Composites Materials," Air Force System Command, DTIC – ADA224926, March 1990.

18. R. Ressl and R Hoye, "Evaluation of a Fluidized-Bed Paint Stripper at Red River Army Depot," Army Corps Engineers, DTIC – ADA250064, April 15, 1992.

19. Thomas E. Higgins and Brian P.J. Higgins, "Industrial Process to Reduce Generation of Hazardous Waste at DoD Facilities," Air Force Systems Command, DTIC – ADA165086, December 1985.

20. Peter W. Kopf and Dean Pichon, "Automated Laser De-Painting System of Aircraft Survey of Enabling Technologies," Air Force Systems Command, DTIC – ADA250380, January 1991.

21. J.P. Murphy and D. Parker, "Engineering Test Report Paint Waste Reduction Fluidized Bed Process Demonstration at Letterkenny Army Depot Chambersburg, Pennsylvania," DTIC – ADA250250, July 1991.

22. Charles C.T. Chen, Mark Muller and John W. Reinhardt "Effects of Plastic Media Blasting on Aircraft Skin," FAA, DTIC – ADA274817, November 1993.

23. "Environmentally Safe and Effective Processes for Paint Removal," AGARD/NATO, DTIC – ADA267003, March 1993.

24. Michael J. Then, "The Future of Aircraft Paint Removal Methods," Department of the Air Force, DTIC – ADA214946, September 1989.

25. Sacramento Air Logistics Center, McClellan AFB, CA, "USAF PRAM Project – Flashlamp De-Paint System," Air Force Systems Command, DTIC – ADA207170, February, 1987.

26. B. Radonich and M. Wells, "Evaluation of Plastic Media Blasting Equipment," Naval Civil Engineering Laboratory, DTIC – ADA208594, April 1989.

27. Mark Muller and Charles C.T. Chen, "Fatigue Testing of 2024-T3 Material After Four Cycles of PMB Stripping," FAA, DTIC – ADA276926, November 1993.

28. James Lukemeyer, "Robotic Paint Stripping Cell," Air Force Material Command, DTIC – ADA279158, November 1993.

29. J. P. Murphy and D. Parker, "Engineering Test Report Paint Waste Reduction – Process Demonstration at Letterkenny Army Depot," US Army Corps of Engineers, DTIC – ADA250955, July 1991.

30. Mike Pawlik, "Xenon Flashlamp Paint Stripping Metallic Substrate Fatigue Testing, Metallic Substrate Fatigue Testing," presented July 16, 1993.

31. David W. Breihan and James Reilly, "Xenon Flashlamp and Carbon Dioxide Advanced Coatings Removal Development and Evaluation Program," prepared for US Navy by McDonnell Douglas Corporation, Report #MDC 93B0341, July 1993.

32. Thomas R. Berkel, "Acoustic Fatigue Testing of the Flashjet Process," Final Report, Boeing-STL 99X0017, August 1999.

33. See Thirty-two.

34. See Thirty-one.

35. G. R. Bonnar, J. R. Hollinger, and Amos Hoggard, "Qualification of Xenon Flashlamp/CO2 Paint Removal Procedures for use on Douglas Commercial Aircraft Components," Douglas Aircraft Company, Report No. 93K0296, March 1993.

36. Wayne N. Schmitz, "Development and Delivery of an F-15 Flashjet Paint Stripping System for Warner Robins Air Logistics Center Phase 1 Engineering Report," McDonnell Douglas Corporation, Report No. MDC 94X0029, October 1994.

37. See Thirty-two.

38. See Thirty-two.

39. L. P. Boyer, T. R. Berkel, and J. P. Walker, "C-17 Weapon System Pollution Prevention Project Risk Assessment Report," Task Order #021 Report, March 1997.

40. "Flashjet Coatings Removal Process".

41. J. D. Head and J. Peter Niedzielski, "Laser Paint Stripping," Air Force Systems Command, WL-TR-91-4026, June 1991.

42. See Forty-one.

43. J. Peter Niedzielski, "Laser Paint Removal System," Air Force Systems Command, WL-TR-93-4113, December 1988.

44. See Forty-three.

45. Materials and Process Partnership for Pollution Prevention, "Final Report for Laser De-coating for Missiles Sub-Task 014," CTC/DP-CL0143-01, January 2001.

46. See Forty-five.

47. J. Woodroffe, et al., "Laser Paint Stripping," Air Force Systems Command, AFWAL-TR-84-4132, March 1985.

48. Tad Tassone, "Stripping with Plastic Media," Industrial Finishing, 63, 14-18, February 1987

49. "Freezing Paint Removal," Industrial Finishing, 60, 30-32, May 1984.

50. Lyle H. McCarty, "Plastic Particles Strip Paint Form Sensitive Surfaces," Design News, 42, 200-202, October 1986.

51. "Chemical/Impact Aerospace Paint Removal System," Aircraft Engineering, 56, 13-14, March 1984.

52. Dr.-Ing. Habil "Coating-Removal Technologies Removal of Thermally Sprayed Coats," Welding Research Abroad, 48, 25-28, March 2002.

53. "Vacu-Blast Custom-Designed Blastroom Reduces Processing Times," Anti-Corrosion, 35, 9, May 1988.

54. James C. Malloy, "Molten Salt Bath Stripping of Organic Coatings," Metal Finishing, 289-294, May 1994.

55. "Engineering and Technical Services for Joint Group on Pollution Prevention (JG-PP) Projects," Joint Test Protocol, J-00-CR-017, February 2001.

56. See Fifty-five.

57. Air Force Test Protocol, "Demonstrate and Validate Specialty Coatings Laser Removal System," Concurrent Technologies Corporation, November 2002.

58. C. Alford, R. C. Decker, D. Forney, R. Hardy, H. Langdon and L. Lockwood, "Evaluation of the Effects of Chemical and Plastic Media Blasting Paint Removal," Air Force Material Command, WL-TR-94-4106, April 1994.

59. "United States Patent, Theodore J. Reinhart," Patent Number 4,836,858, June 1989.

60. George P. Joyce, "A Comparative Analysis of Two Alternates to Chemical Aircraft Paint Stripping," Master Thesis, DTIC – ADA325115, December 1996.

61. K. G. Clark and S. J. Spadafora, "Investigation of Coating Systems and Removers for Graphite/Epoxy Composite Surface," Air Systems Command, DTIC – ADA325778, June 1984.

62. Terry Foster, Olivier Malavallon, and S. Visaisouk, "Environmentally Safe and Effective Processes for Paint Removal," Foster, AGARD/NATO, AGARD-LS-201, July 1995.

63. Warner Robins AFLC, "Carbon Dioxide Pellet Blasting Augmented Xenon Flashlamp Coatings Removal Design and Prototype Demonstration Project, PRAM Project," DTIC – ADA331833, March 1993.

64. Department of Defense, "Air Force Aircraft Painting and Corrosion Controls," DTIC – ADA371306, January 1996.

65. Shelton R. Young, John A. Gannon, Geraled P. Montoya, John W. Sullenberger, and Timothy J. Harris, "U.S. Marine Corps Aircraft Corrosion Prevention and Control Program," Department of Defense, DTIC – ADA369959, October 1996.

66. Joseph Kozol, Dayle Conrad, Steven Hartle, Gary Neumeister and Stephen Spadafora, "Aircraft Depainting Technology," US Navy, DTIC – ADA362188, March 1999.

67. John J. Jusko, "Surface Analysis of Anodized Aluminum Panels that have been Painted, Bead Blasted, Cleaned and Treated with a Chemical Conversion Coating, Proceedings of Tri-Service Conference on Corrosion, DTIC – ADA331220, June 1994.

68. Howard J. Storr, "Effect of Plastic Bead Blasting Paint Removal Process on the Fatigue Lives of Thin Skin Materials," AFWAL, DTIC – ADA326371, May 1988.

69. Barry S. Spiegel, Janet Buchingham, and Craig McClung, "Evaluation of Envirostrip for Depainting Thin-Skinned Aluminum Alloys," Air Force Material Command, DTIC – ADA392371, October 2000.

70. Joseph Kozol, Steven Hartle, Paul Raley and Thomas Berkel, "Flashjet Qualification Testing for Lifecycle De-painting of Rotary Wing Fuselage Skins," Naval Air Warfare Center, April 2001.

71. Richard Schmid, "Advances in Ultra-High-Pressure Waterjetting," <u>Journal of Protective Coatings & Linings</u>, 14, 82-86, February 1997.

72. John Oestreich and Todd Porter, "Starch Media Blasting for Aerospace Finishing Applications," <u>Metal Finishing</u>, 15-18, March 1993.

73. Robert A. Roberts, "Paint Removal Through Plastic Media Blasting – A Dream Come True," SAE Technical Paper #860703, 22nd Annual Airline Plating and Metal Finishing Forum, Seattle, February 1986.

74. Joseph Kozol, Dayle Conrad, and Steve Hartle, "21st Century Aircraft De-painting Strategies," Proceedings of 42nd International SAMPE Symposium, 42, 677-688, May 1997.

75. David P. Widauf, "The Evaluation of the Effects of a Plastic Bead Blasting Paint Removal Process on Graphite/Epoxy Composites," Proceedings of 36th International SAMPE Symposium, 36, 325-355, April 1991.

76. K. T. Juey, D. J. Coleman, G. K. Turnet, "Replacement of Methylene Chloride in NVR and Paint Removal Applications," DTIC - ADA388362, December 2000.

77. Charles H. Cundiff and Janet Buckingham, "C-130 Flight Control Surfaces De-paint process Optimization," Air Force Material Command, AFRL-ML-WP-TR-2000-4120, December 1999.

78. Stanton E. Collier, "Paint Removal Process," Collier, Stanton E., Department of the Air Force, ADD012167, December 1985.

79. Charles H. Cundiff and Jason R. Varner, "Evaluation of Selective Stripping Technology," Air Force Material Command, DTIC – ADA386462, September 2000.

80. Joseph Kozol, Qualification of an Environmentally Safe and Effective Paint Removal Process for Aircraft, Naval Air Warfare Center, DTIC – ADA385353, August, 1999.

81. Shelton R. Young, Christian Hendricks, James L. Kornides, Vickie Nguyen, and Kathleen M. Rinaldi, Audit Report, Office of the Inspector General, "Air Force Study on Paint Stripping Technology," Department of Defense, Report No. 93-086, DTIS – ADA376743, April 1993.

82. Shelton R. Young, Gordon P. Nielsen, Christian Hendricks, James L. Kornides, Gerald P. Montoya and Elizabeth A. Freitag, Audit Report, Office of the Inspector

General, "Quick Reaction Report on Repainting of the C-5 Aircraft." Department of Defense, Report No. 94-198, September 1994.

83. Omar Deel, "Plastic Media Blasting," Air Force Material Command, WL-TR-95-4049, March 1995

84. D. J. Stevenson, S. A. Impey, M. Malik and P. Hancock, "Modeling Initiation of Surface Damage on Aluminum by High Velocity Water Jets," <u>Material Science and Technology</u>, 9, 869-873, October 1993.

APPENDIX B

TENSILE RESULTS

90% C.I. Statistical
Significance - √

PLCRS and Reference Data
Average Ultimate Tensile Strength Results, 2024-T3 Clad

PLCRS
Thickness-0.025"

Reference (2)
Thickness -0.032"

MMPDS Handbook
'A' Allowable = 60

Stress [ksi]

baseline · CO2 · Nd YAG (C) · Nd YAG (Q) · baseline · DMB (Wheat Starch)
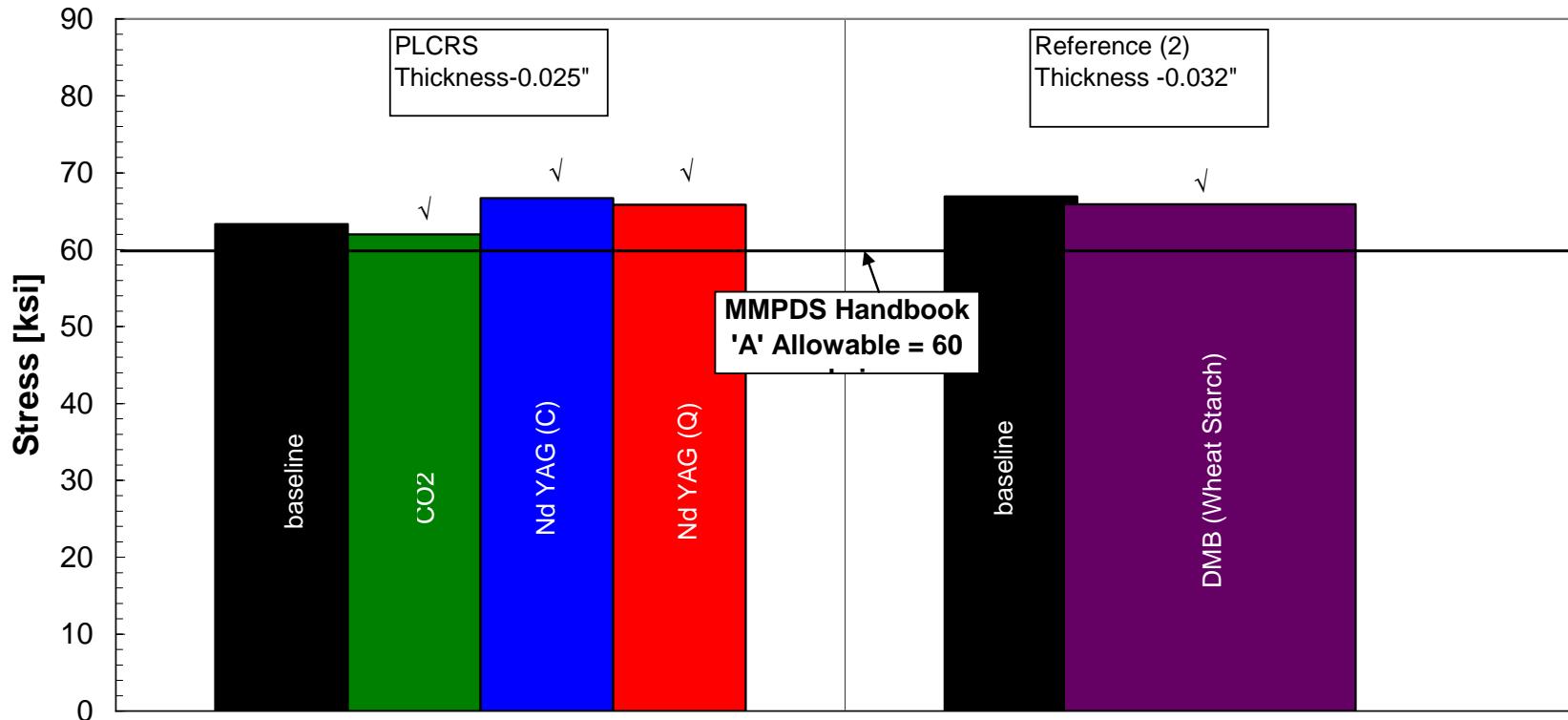
**Figure B1. PLCRS and Reference Data Metallic Al 2024-T3 Clad Ultimate Tensile Strength Results.**

90% C.I. Statistical Significance - √

**PLCRS and Reference Data
Average Yield Tensile Strength Results, 2024-T3 Clad**

PLCRS
Thickness-0.025"

Reference (2)
Thickness - 0.032"

**MMPDS Handbook 'A'
Allowable = 44 ksi**

Strength [ksi]

baseline
CO2
Nd YAG (C)
Nd YAG (Q)
baseline
DMB (Wheat Starch)
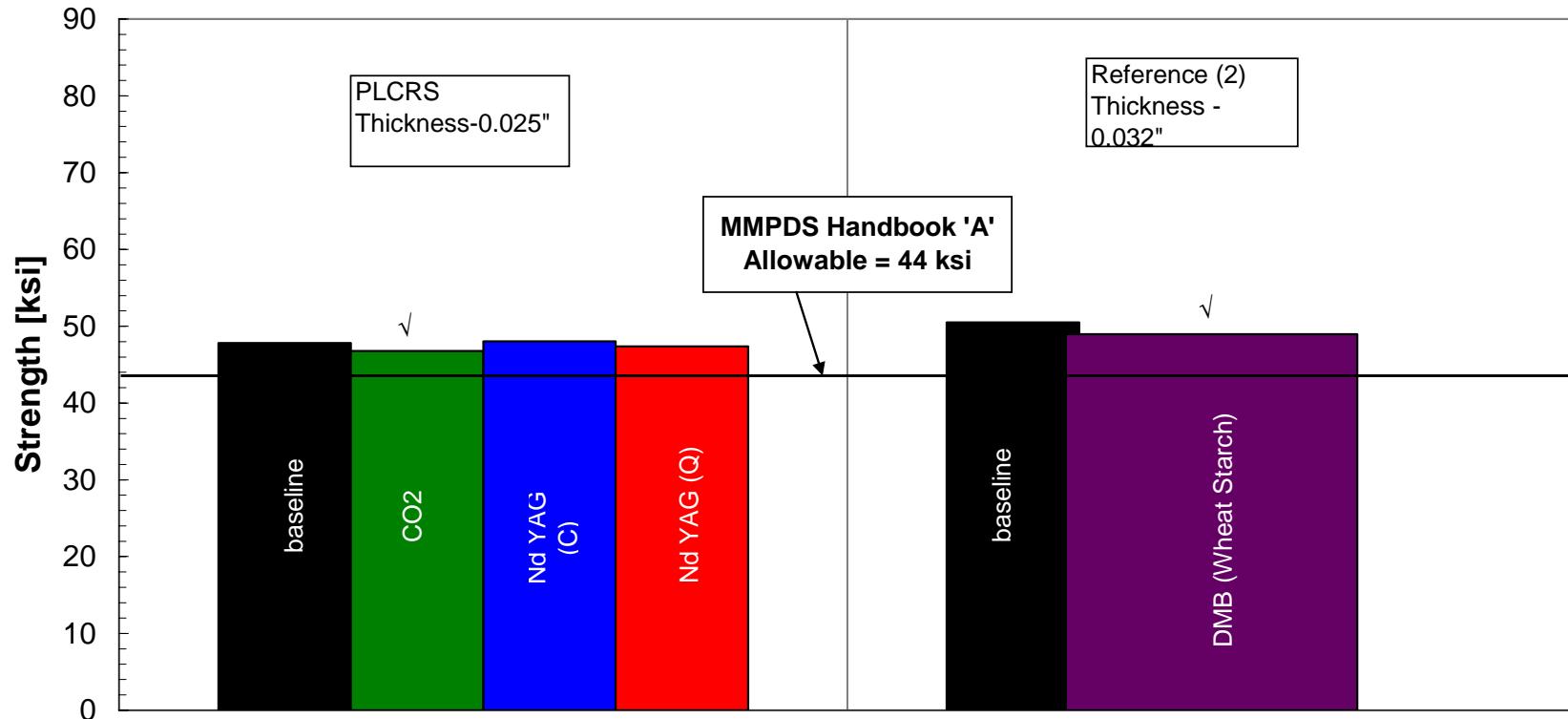
Figure B2. PLCRS and Reference Data Metallic Al2024-T3 Clad Yield Tensile Strength Results.
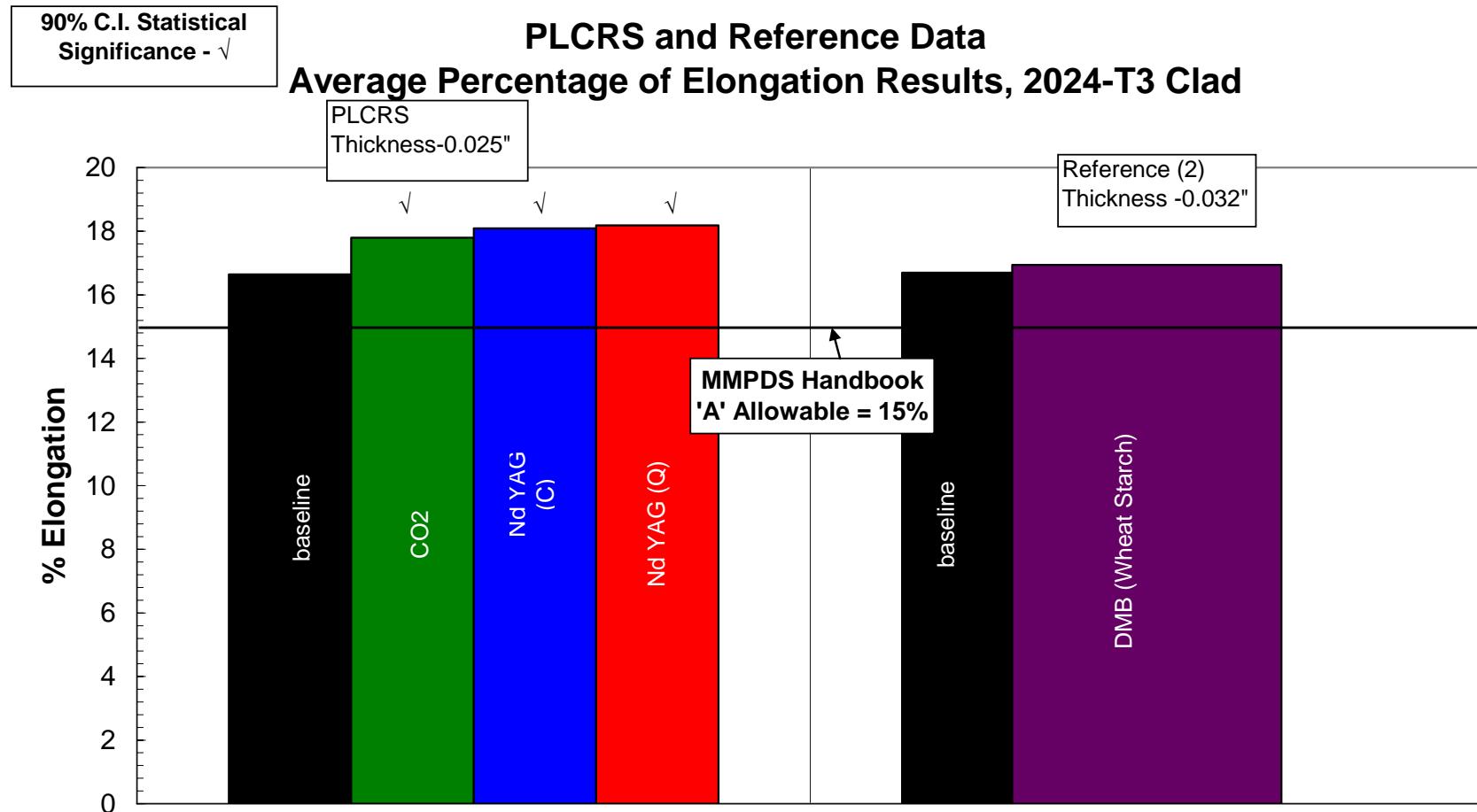
Figure B3. PLCRS and Reference Data Metallic Al2024-T3 Clad Elongation Results.

Figure B4. PLCRS and Reference Data Metallic Al7075-T6 Bare Ultimate Tensile Strength Results.

Figure B5. PLCRS and Reference Data Metallic Al7075-T6 Bare Yield Tensile Strength Results.
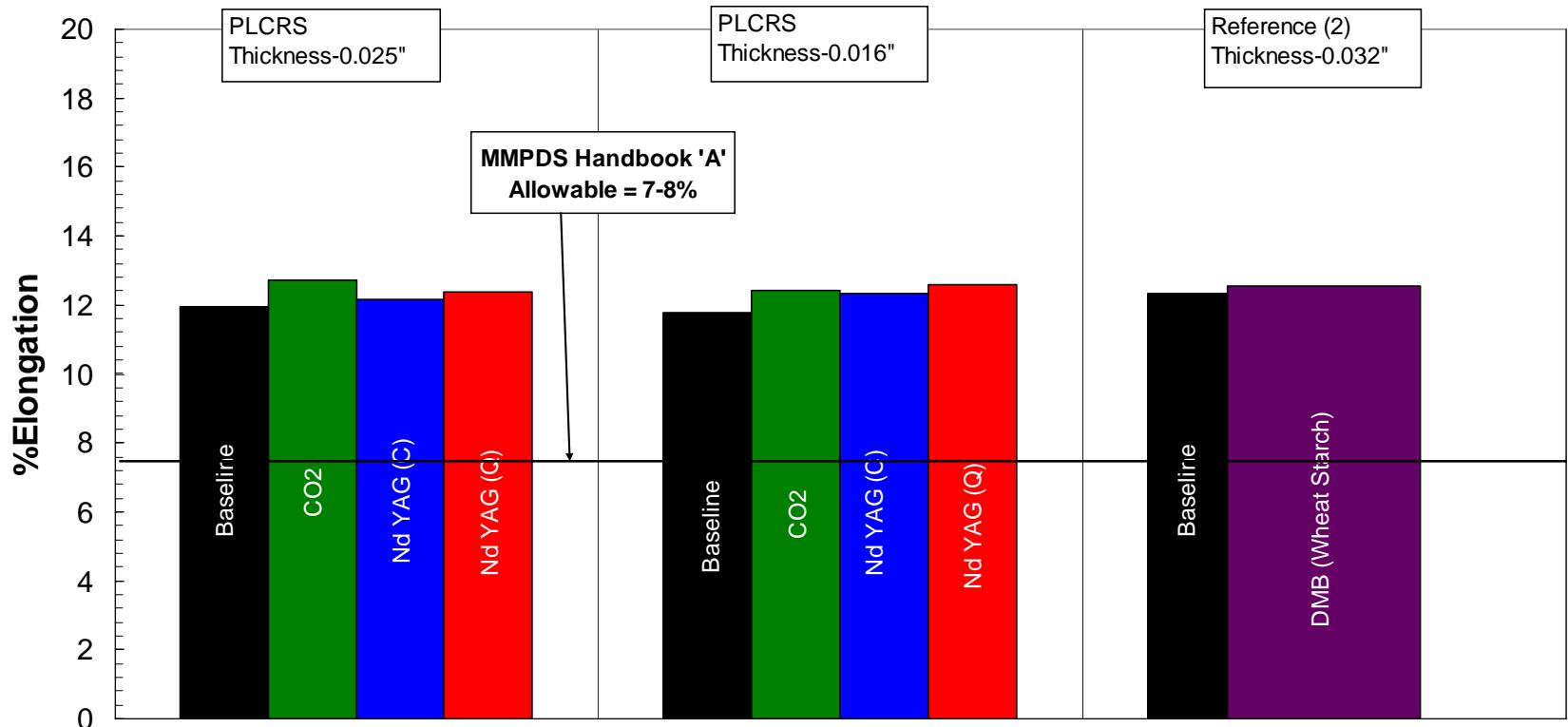
Figure B6. PLCRS and Reference Data Metallic Al7075-T6 Bare Elongation Results.

90% C.I. Statistical Significance - √

PLCRS and Literature Search Data
Average Ultimate Tensile Strength Results, 7075-T6 Clad

PLCRS
Thickness-0.025"

Reference (2)
Thickness -0.032"

MMPDS Handbook
'A' Allowable = 71 ksi

Strength [ksi]

Baseline
CO2
Nd YAG (C)
Nd YAG (Q)
Baseline
DMB (Wheat Starch)
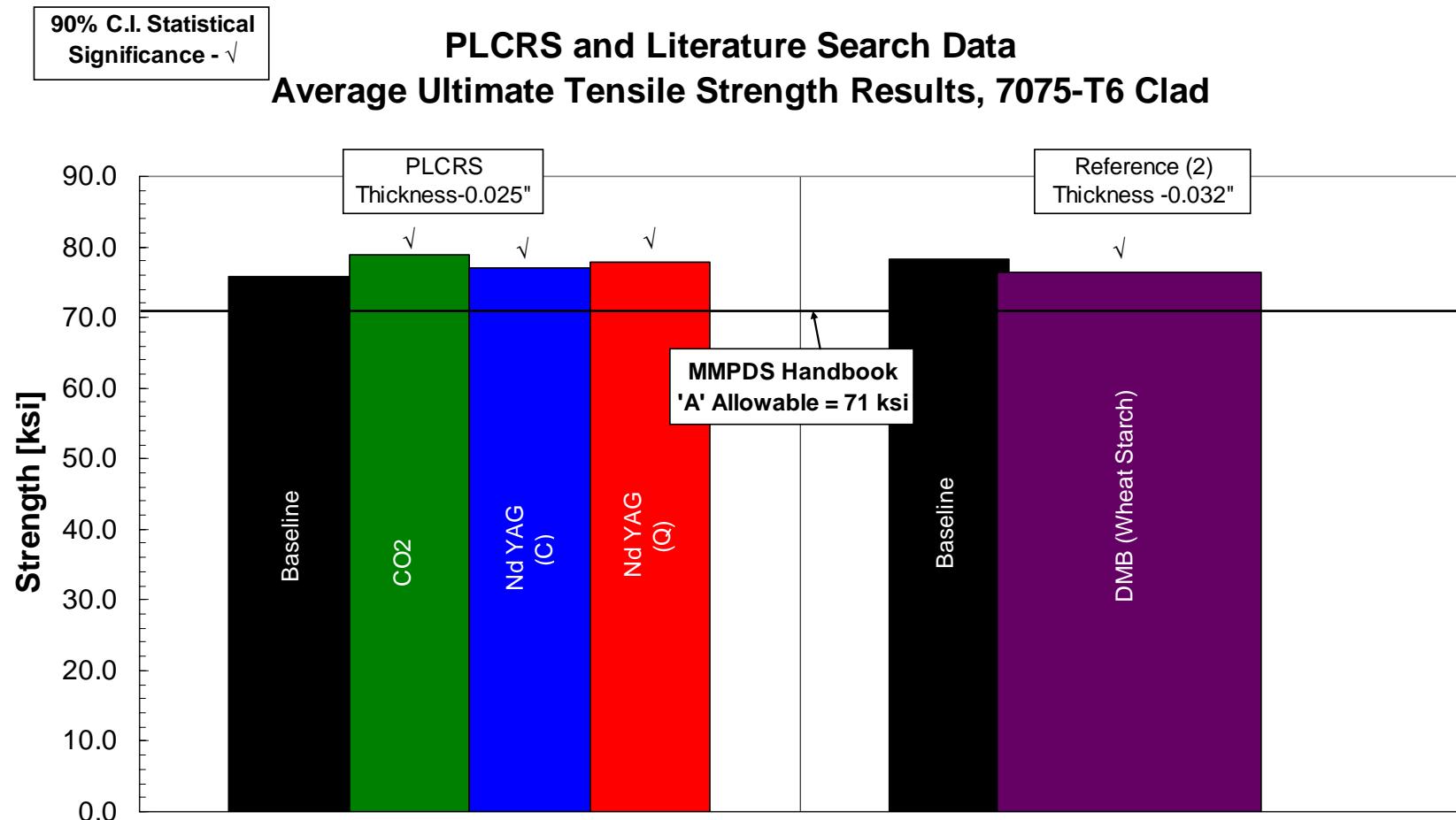
Figure B7. PLCRS and Reference Data Metallic Al7075-T6 Clad Ultimate Tensile Strength Results.
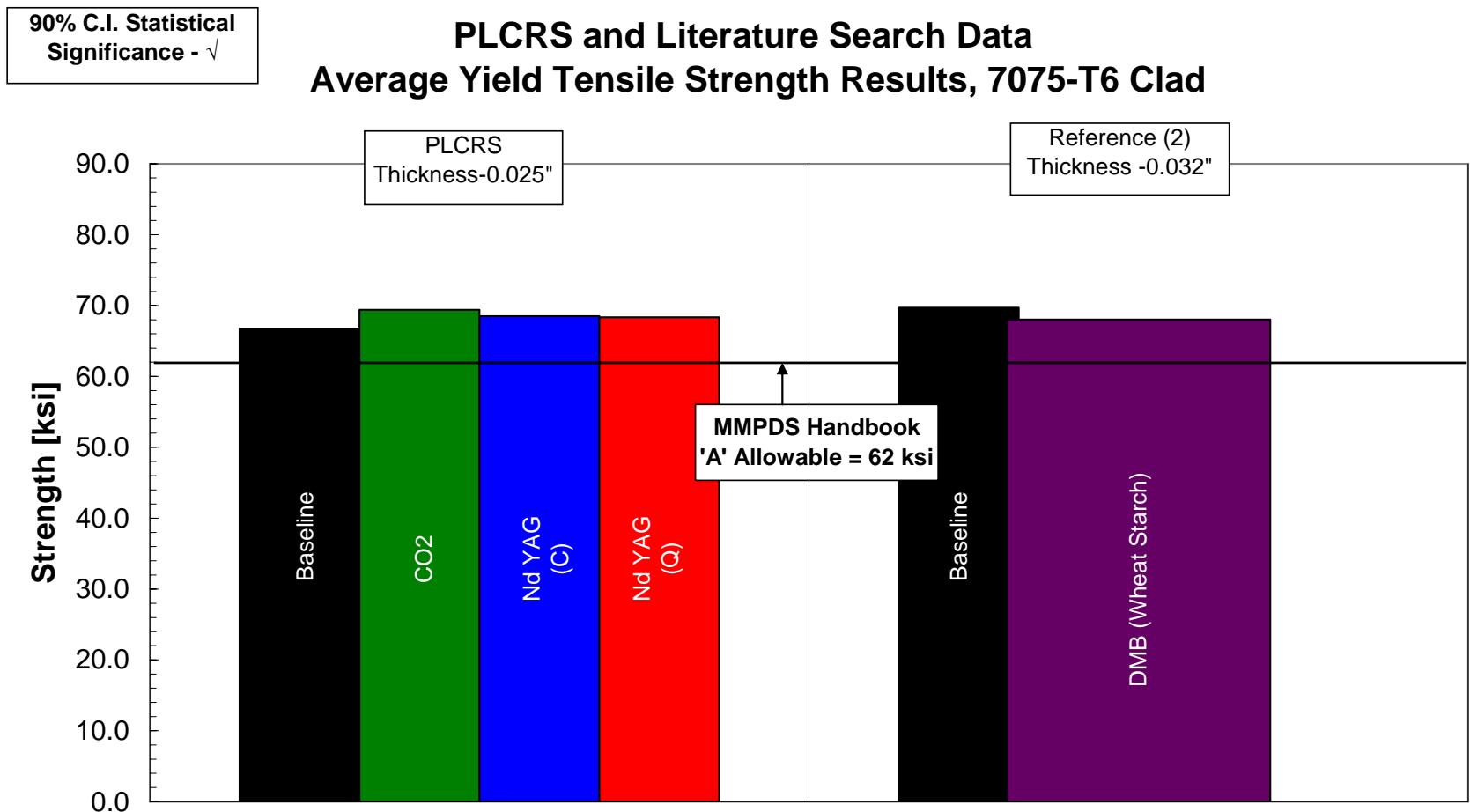
Figure B8. PLCRS and Reference Data Metallic Al7075-T6 Clad Yield Tensile Strength Results.
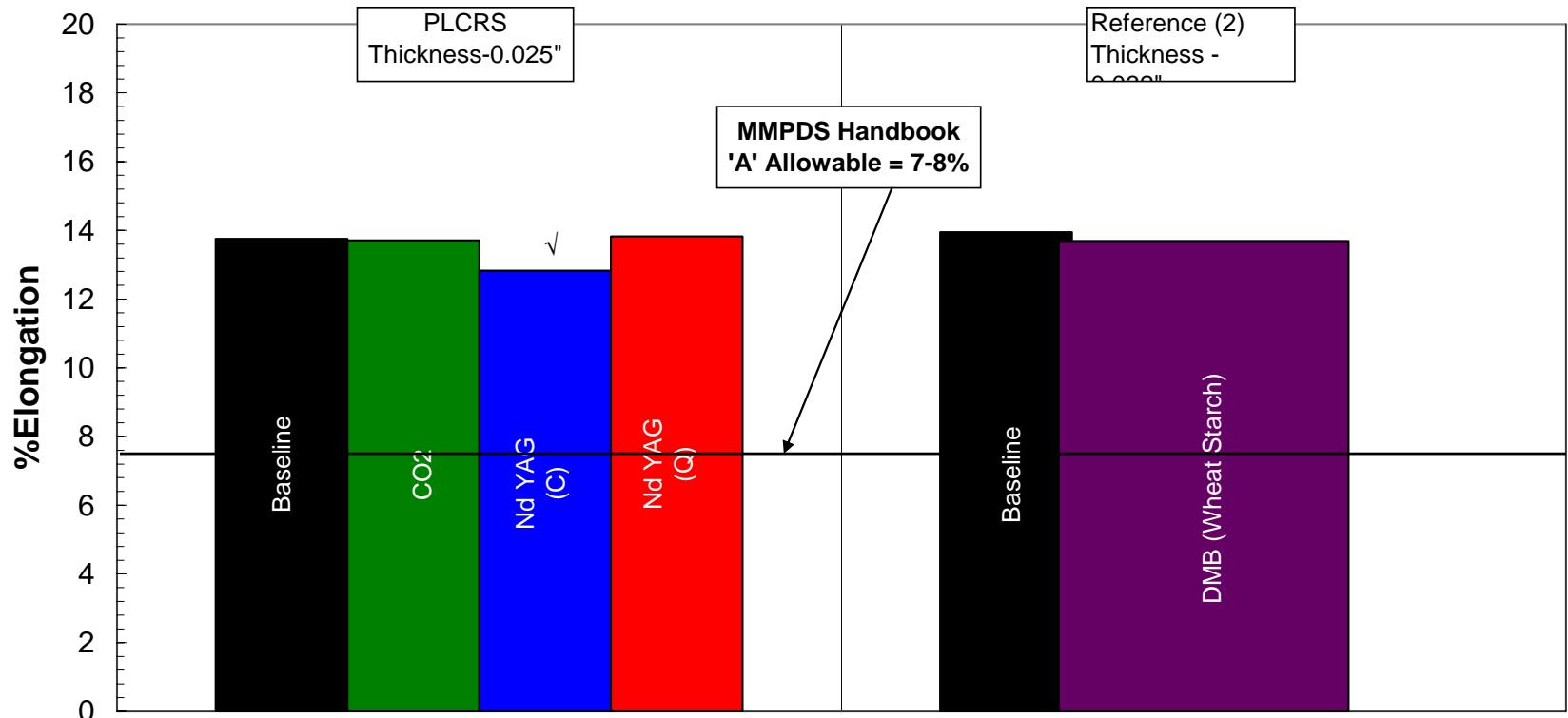
Figure B9. PLCRS and Reference Data Metallic Al7075-T6 Clad Elongation Results.

Reference Data for Tension Testing

Reference (3) - "Mechanical Behavoior of Al 2024 All0y Specimen to Paint Stripping by Laser Radiation and Plasma Ecthing"

		UTS	Std Dev	YTS	Std Dev	%Elog	Std Dev	- Number of sample
Baseline	Al 2024-T3Bare	70.05076		47.86077		17.68		5
TEA-CO2 laser	Al 2024-T3Bare	68.8905		45.54025		16.4		5
CO2 laser	Al 2024-T3Bare	68.74547		45.54025		13.1		5
YAG laser	Al 2024-T3Bare	68.96302		46.84554		12.85		5
Excimer laser	Al 2024-T3Bare	68.60044		46.48296		11.6		5
Plasma etching	Al 2024-T3Bare	67.15011		47.9913		3.08		5

Reference (2) - "Evaluation of Envirostrip for De-painting Thin-Skinned Aluminum Alloys"

		UTS	Std Dev	YTS	Std Dev	%Elog	Std Dev	- Number of sample
Baseline	Al 2024-T3Bare	72.83	0.1	53.94	0.24	16.93	0.44	4
Envirostrip	Al 2024-T3Bare	72.19	0.25	52.67	0.14	18.06	0.49	4
Baseline	Al 2024-T3Clad	66.91	0.38	50.48	0.39	16.70	1.00	4
Envirostrip	Al 2024-T3Clad	65.93	0.25	48.97	0.09	16.94	0.78	4
Baseline	Al 7075-T6Bare	85.41	0.37	79.32	2.23	12.33	0.75	4
Envirostrip	Al 7075-T6Bare	83.65	0.29	76.06	0.31	12.55	0.26	4
Baseline	Al 7075-T6Clad	78.28	0.4	69.68	1.11	13.95	0.64	4
Envirostrip	Al 7075-T6Clad	76.38	0.09	68.03	0.11	13.69	0.54	4

Reference (1) - "Laser Paint Stripping"

|		UTS	Std Dev	YTS	Std Dev	%Elog	Std Dev	- Number of sample
Baseline	Al 2024-T3Bare	64960		63590		16.3		
		64750		64400		16.7		
		65470		64390		17		
		65109		63520		16.4		
		65070		65030		11.6		
	Avg.	*65071.8*		*64186*		*15.6*		
	Std Dev.	*262.6808*		*632.163*		*2.252776*		
CO2	Al 2024-T3Bare	66980		65260		15.6		
		65060		63450		16.1		
		64790		62990		17.1		
		67330		65580		16.3		
		65250		64210		18.6		
		64660		63360		16.3		
		64540		63290		15.5		
		66570		64480		16.2		
		67080		65560		16.2		
		67330		65580		16		
	Avg.	*65959*		*64376*		*16.39*		
	Std Dev.	*1193.04*		*1059.929*		*0.890006*		

APPENDIX C

FATIGUE RESULTS
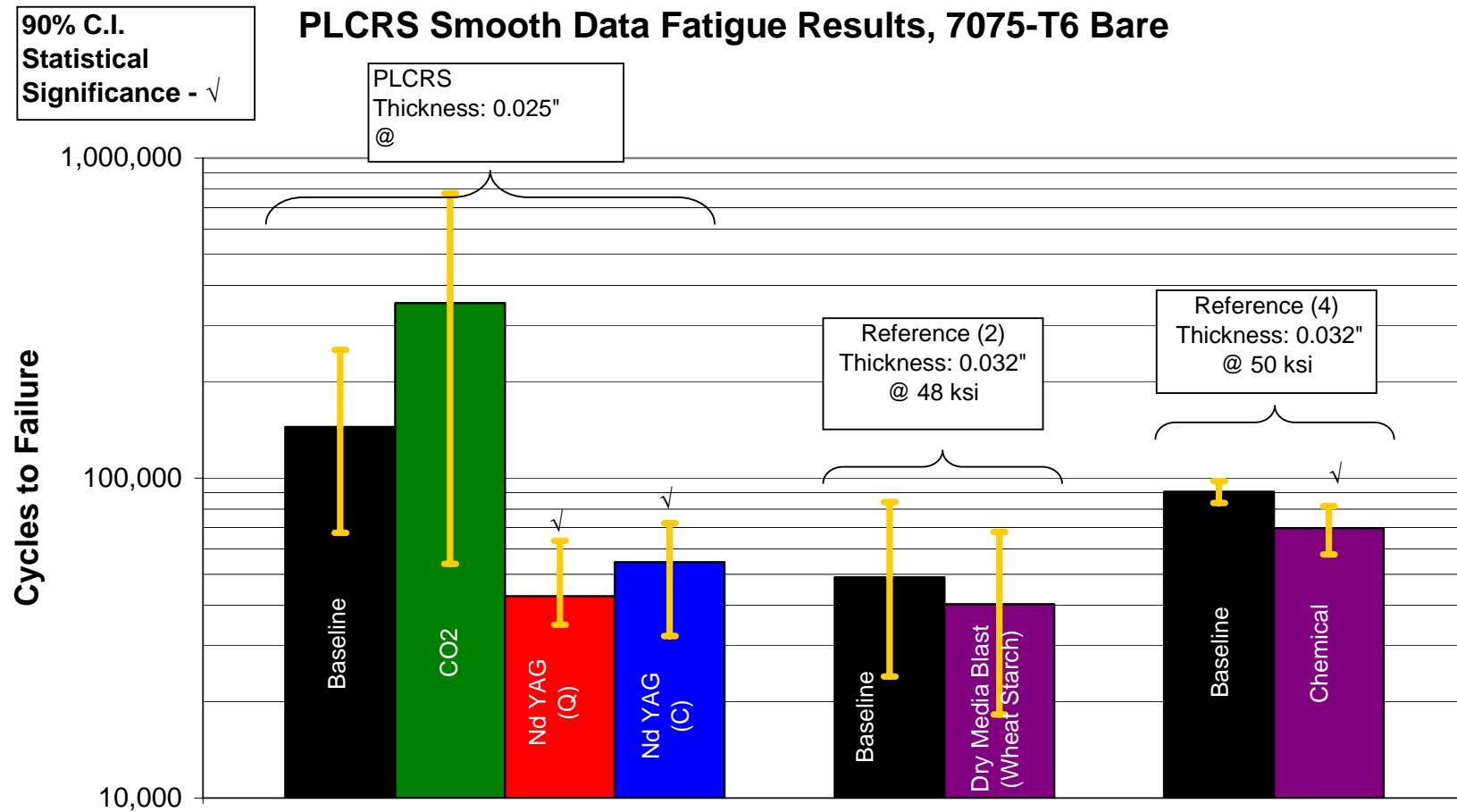
Figure C1. PLCRS and Reference Data 7075-T6 Bare Smooth Fatigue Results. √ indicates a statistical difference at a 90% simultaneous confidence level.

Figure C2. PLCRS and Reference Data Metallic Al7075-T6 Bare Notch Fatigue Results.
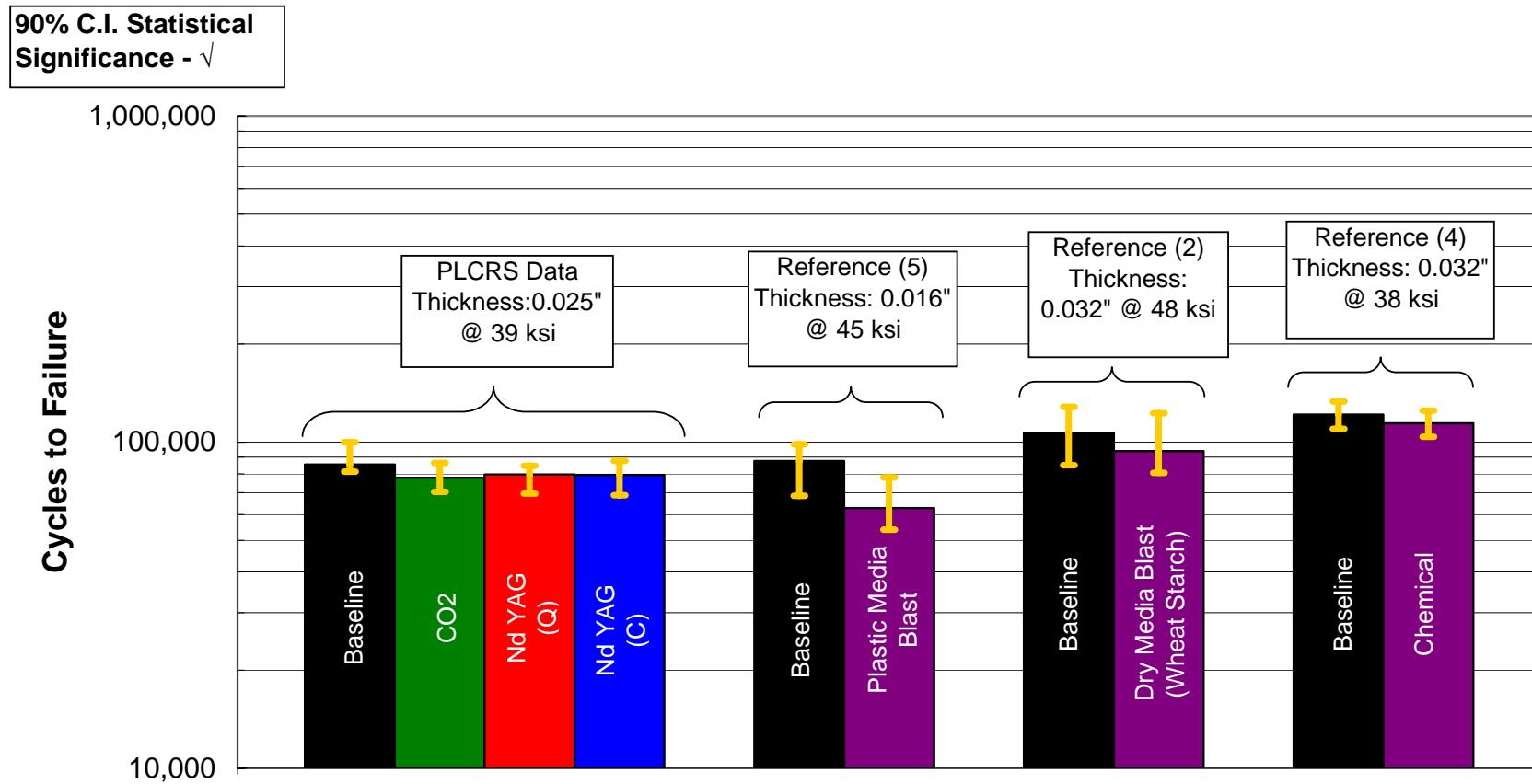
**Figure C3. PLCRS and Reference Data Metallic Al7075-T6 Clad Smooth Fatigue Results.**

Figure C4. PLCRS and Reference Data Metallic Al7075-T6 Clad Notch Fatigue Results.

7075-T6 Bare Smooth Fatigue Data

Reference (4)

		Average		N - Number of Samples
Control	83,588			
	97,772	90,680	4.957512	12
Chemical	57,671			
	81,641	69,656	4.842959	8

Reference (2)

	Average	Std Dev	Average	Std Dev	
Control	48,937	17,662	4.689637	4.24704	10
Envirostrip	40,300	17,484	4.605305	4.242641	10

7075-T6 Clad Fatigue Data

Smooth

Reference (5)

Control	68,500		
	96,000		
	98,500	87,667	4.942834
PMB	78,000		
	56,700		
	53,900	62,867	4.79842

Reference (2)

	Average	Std Dev	Average	Std Dev	N - Number of Samples
Control	106,900	13,762	5.028978	4.138682	10
Blasted	93,852	14,361	4.972444	4.157185	10

Reference (4)

				N - Number of Samples
Control	109,903			
	133,147	121525	5.084666	12
Chemical	103,928			
	124,872	114400	5.058426	8

Notch

Reference (6)

Control (30 ksi)	20,614		
	19,573		
	20,639		
	22,254	20,770	4.317436
Stripped (30 ksi)	17,811		
	20,000		
	18,134		
	23,727	19,918	4.299246
Control (20 ksi)	91,787		
	78,845		
	78,900		
	73,585	80,779	4.9073
Stripped (20 ksi)	82,389		
	116,427		
	79,536		
	110,634	97,247	4.987874

2024-T3 Clad Fatigue Data

Smooth and Notch

Reference (5)

Control	67,237		
	74,111		
	101,700		
	76,676		
	83,929		
	94,228		
	87,327		
	100,758		
	77,394		
	93,755	86,518	4.937104
PMB	36,584		
	67,527		
	80,355		
	77,450		
	45		
	27,665		
	49,075		
	72,499		
	91,650		
	61,220	56,407	4.751333
PMB	82,998		
	76,923		
	84,479		
	69,337		
	94,511		
	50,500		
	71,024		
	68,562		
	88,300		

Reference (2)

	Cycles	Std Dev	Cycles	Std Dev	N - Number of Samples
Control	100157	10494	5.000681	4.02094106	10
Blast	66500	11281	4.822822	4.052347599	10

Reference (4)

				N - Number of Samples
Control	112,854			
	121,860	117357	5.069509	12
Chemical	82,601			
	104,007	93304	4.9699	8

Reference (6)

Control (30 ksi)	39,929		
	30,408		
	27,608		
	23,025	30,243	4.48062
	24,666		
Stripped (30 ksi)	30,615		
	44,508		
	28,100	31,972	4.50477
	126,649		
Control (20 ksi)	173,515		
	163,970		
	147,424	152,890	5.18438
	141,938		
Stripped (20 ksi)	168,236		
	153,498		
	143,788	151,865	5.18146

APPENDIX D

FATIGUE CRACK GROWTH RATE RESULTS

Figure D1. PLCRS Fatigue Crack Growth Rate Metallic Al7075-T6 Clad Results.

Figure D2. Metallic Al 7075-T6 Clad Fatigue Crack Growth Rate Statistical Analysis at ΔK of 6 and 14.

**PLCRS Fatigue Crack Growth Rate Results, 7075-T6 bare (0.016")
Paint System #05**
(Mil-PRF-23377 primer/PRF-85285 topcoat) unless noted
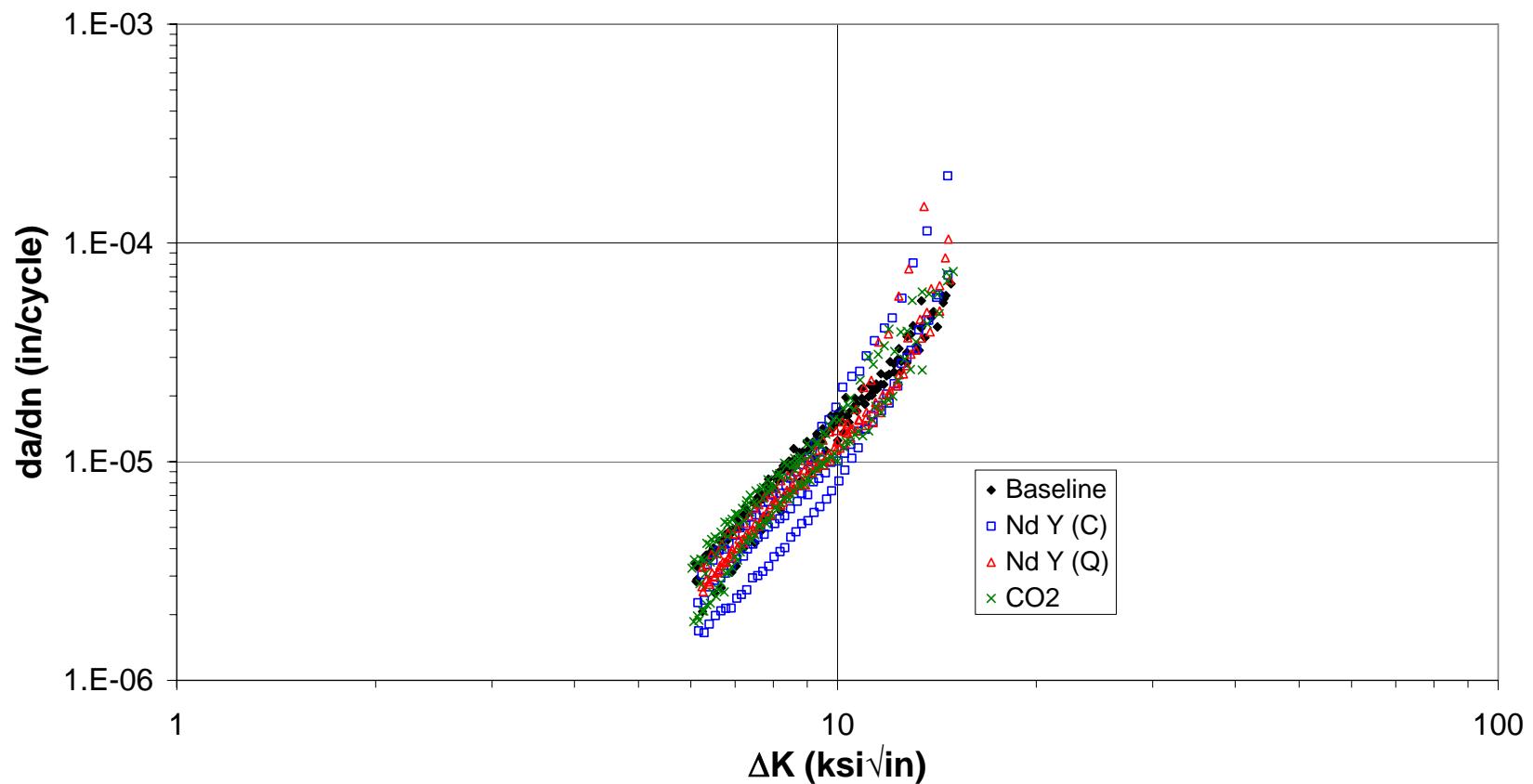
**Figure D3. PLCRS Fatigue Crack Growth Rate Metallic Al7075-T6 Bare Results.**
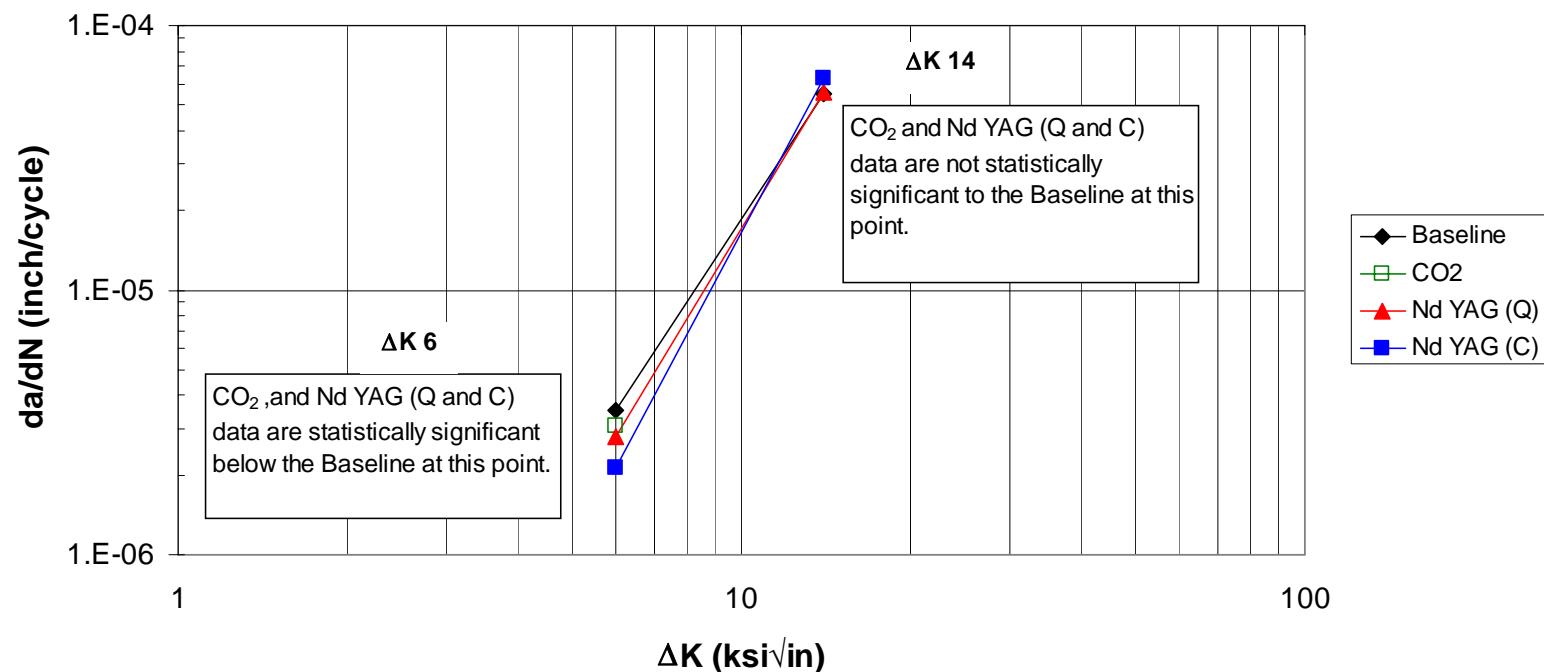
Figure D4. Metallic Al 7075-T6 Bare Fatigue Crack Growth Rate Statistical Analysis at ΔK of 6 and 14.

APPENDIX E

FLEXURAL STRENGTH RESULTS
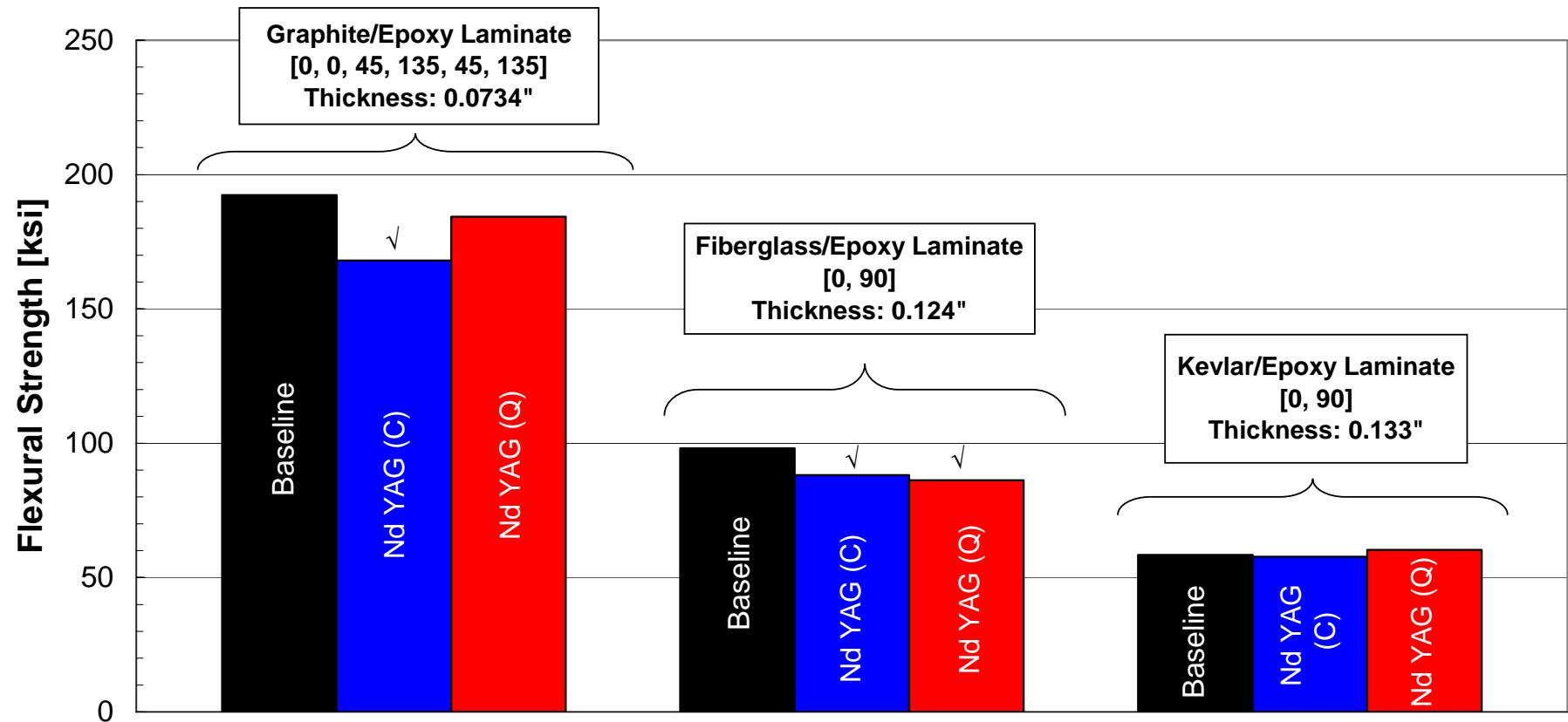
Figure E1. PLCRS Flexural Strength Results.

90% C.I. Statistical
Significance - √

PLCRS and Reference Data
Flexural Strength Results, Graphite/Epoxy Laminate
(Compression)

PLCRS
[0,0,45,135,45,135]
Thickness: 0.0734"

Reference (5)
AS4/3501-6 [0,+/-45,0,90,0]
Thickness: 0.0780"

Flexural Strength [ksi]

Baseline
Nd YAG (C)
Nd YAG (Q)
Baseline
PMB One Cycle @ 38 psi
PMB Two Cycle @ 38 psi
PMB Four Cycle @ 38 psi
PMB One Cycle @ 60 psi
PMB Two Cycle @ 60 psi
PMB Four Cycle @ 60 psi
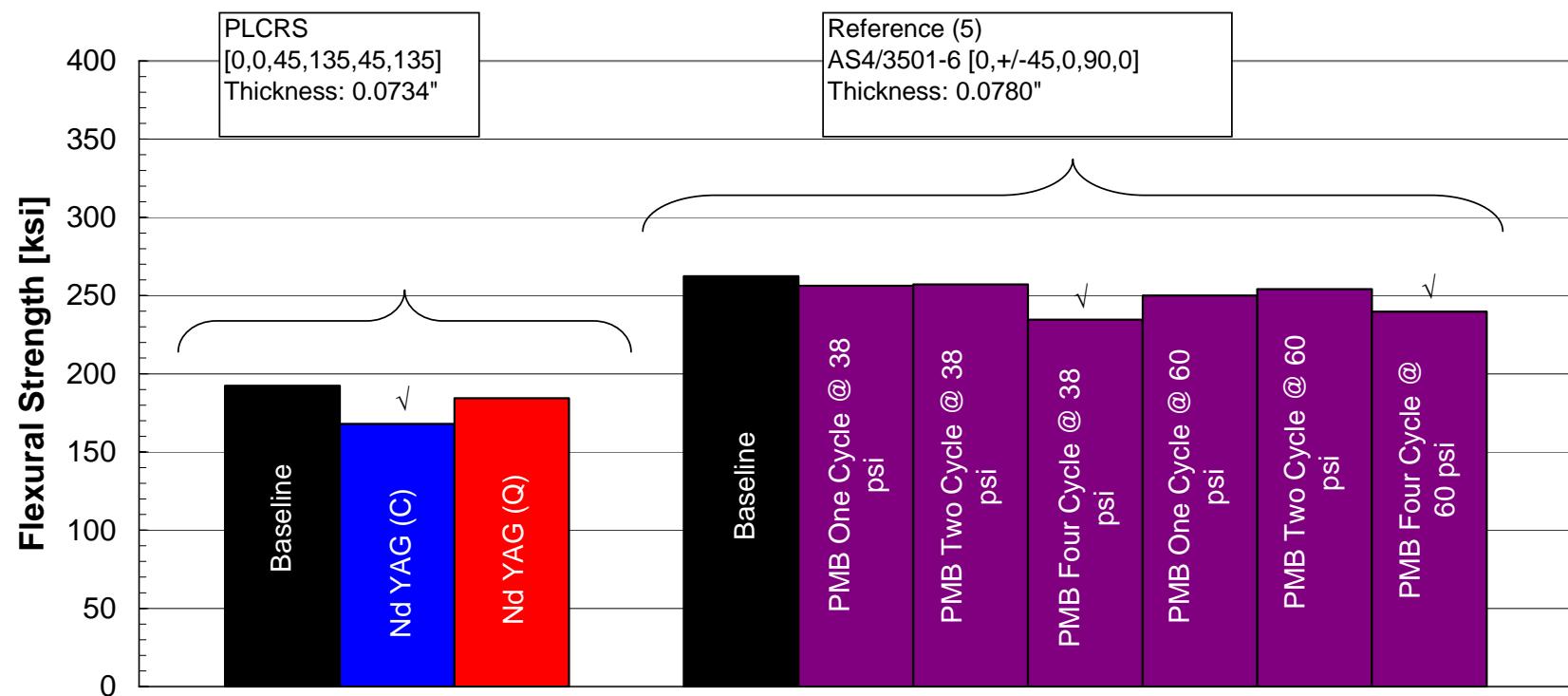
Figure E2. PLCRS and Reference Data Flexural Strength Results.

Reference Data for Flexural Strength

Reference (7)

Wet Abrasive		Average Flexural Strength
Baseline	-	140.4
Substrate	-	156.3

Bicarbonate		Average Flexural Strength
Baseline	-	150.1
Substrate	-	171.4

Abrasive		Average Flexural Strength
Baseline	-	143.7
Substrate	-	146.4

Reference (5)

PMB

	Number of Specimen	Average Strength	Std. Dev.
Baseline	7	161.78	6.87
One @ 38	8	157.15	17.74
One @ 38	6	146.67	13.37
Two @ 38	9	149.60	12.47
Four @ 38	10	158.49	15.39
One @ 60	8	153.91	14.62
Two @ 60	9	144.45	11.37
Four @ 60	7	142.68	9.70

Reference (9)

Flash lamp

	Number of Specimen	Average Strength	Std. Dev.
Baseline	12	221.1	8.0
Substrate	12	210.2	8.0